Improving the Stability of a Gas-liquid Spray by Modifying the Two-phase Flow Pattern Entering the Nozzle

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Abstract
An investigation of how changes to the feeding conduit of a gas-liquid spray nozzle can widen the stable operating regime is presented in this work. The concept is based on maintaining a thorough mixing of the two phases, resulting in a more homogeneous flow pattern entering the nozzle. The modification consists of a series of abrupt changes in the inner diameter of the feeding pipe. This alternative is experimentally compared with the standard conduit in terms of their effect on the spray stability. A full-scale testing system was used with water and air as fluids. The range of flow conditions considered was 76–182 kg/min of water and 1–3 kg/min of air, which corresponds to 0.55–3.96 % of air to liquid mass ratio. The stability was indirectly assessed through the analysis of the pipe wall pressure fluctuations. Specifically, a criterion was established based on the area beneath the power spectral density of the pressure fluctuation signal, for frequencies below 40 Hz. This value increases significantly when the system passes from stable to unstable conditions, allowing the determination of a stability transition line. In addition, qualitative techniques were employed to examine the spray stability based on the spray visualization through direct observation and video recording. The feeding pipe consisting of abrupt diameter changes displayed a good improvement in the stability range of the system, offering the possibility of maintaining a stable spray while decreasing the water flow rate to around 15–40 kg/min for a constant air flow, from the current stability transition. A small increment in the pressure drop was found to range between 3 and 25 kPa.

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Introduction

Atomization of liquids with the assistance of gas is used in several industrial processes, such as the case of the fluid coking process where a mixture of bitumen and steam is sprayed through nozzles into a fluidized bed of coke particles. The principle of operation of the fluid coking nozzle is similar to that of classical effervescent atomizers, defined by mixing the gas and liquid prior to the nozzle exit. Typically, in effervescent atomization the gas is mixed with the liquid within the body of the atomizer, whereas in fluid coking the gas and liquid are mixed well upstream of the atomizer and flow through a pipe to the nozzle. One of the drawbacks found with both types of nozzles, is the development of instabilities in the spray caused by the two-phase flow pattern formed inside or upstream the nozzle [1, 2, 3, 4]. A homogeneous mixture, with gas bubbles well dispersed in the liquid phase, maximizes the effect of the gas phase decompression, resulting in a stable spray with a well atomized and properly distributed liquid phase. In contrast, a non-homogeneous or intermittent flow generates an unstable spray characterized by intermittency in its pattern, with an alternate presence of fine and coarse spray.

The uneven distribution of the unstable spray pattern has a detrimental effect on the process for which the spray is produced. For instance, in the case of the fluid coking process where the liquid is sprayed into a fluidized bed, the intermittency of sections with high and low liquid dispersion can favor the formation of liquid-particle agglomerates. An unstable spray has also been shown to reduce the entrainment rate of fluidized solids into the jetting region [5]. Because of the detrimental effects of an unstable spray, operation of the nozzle in this regime is undesired.

The effect of the two-phase flow on the spray stability is promoted in the case of the nozzle used in fluid coking, by the location of the mixing device well upstream the nozzle. This is because the coalescence of bubbles is favored with the flow of the two-phase mixture through the feeding pipe installed between the mixing point and the atomizer. Lower liquid flow rates, relative to the gas flow rate, tend to promote the appearance of intermittent flow patterns along the feeding pipe, resulting in an unstable spray. On the other hand, experimental evidence has shown improvements in atomization when using higher amounts of gas relative to the liquid phase. For instance, Whitlow and Lefebvre [1] found that for effervescent atomizers operating in the bubbly flow regime the spray Sauter mean diameter (SMD) decreases for higher ALR or operating pressure.

The main objective of this study is to examine how changes to the geometry of the feeding pipe can widen the stability range of gas-liquid sprays issued from nozzle assemblies as the one employed in fluid coking. This would facilitate the use of higher amounts of gas with respect to the liquid phase without reaching unstable conditions. The approach followed was focused on altering the two-phase flow structure entering the nozzle through modifications to the feeding pipe. The concept is based on breaking-up the bubbles and enhancing the mixing between the gas and liquid phases through a series of abrupt changes in the inner diameter of the conduit. This is compared to the standard pipe in terms of spray stability and pulsation strength. The stability is indirectly assessed using analysis of pressure fluctuations, and supported by the use of qualitative techniques, such as direct observation of the spray, regular-speed and high-speed videos.

Equipment and experimental procedure

The experiments were conducted in a commercial-scale spray testing facility at the Syncrude Research Center (Edmonton, Alberta). In this facility, the liquid is supplied by centrifugal pumps, while the gas is delivered by a reciprocating compressor. The liquid and gas are combined in a mixing device and then flow to the nozzle through the feeding pipe. The spray generated by the nozzle is discharged into a liquid collector tank, from where the liquid is recirculated into the system. The nozzle is a patented design (US patent 6 003 789). The mixing device and the considerations for its design are presented in Chan et al. [7].

The conduit or feeding pipe is a 100 cm long steel pipe, schedule 80 with 2.43 cm of internal diameter. The proposed alternative consists of two sudden expansion-contractions of the pipe cross-section. To implement it, commercially available reducing couplings were used to alternately connect pipe sections of 2.43 cm ID with sections of 3.81 cm ID and 7 cm long. The length of the small diameter sections was such that the total length of the arrangement was 100 cm. This change in diameter represents a 150 % of increment in the flow area. Figure 1 depicts schematics of the set-up.

Dynamic pressure measurements were performed along the feeding pipe using piezoelectric transducers, which were mounted flush with the inside pipe wall. These transducers are labeled as D1, D2, D3 in Figure 1. D1–D2, and D3 correspond to the models PCB 113A21 and PCB 112A04 with measurement ranges of 0–1379 and 0–690 kPa, and
the range of 0.31 to 0.81.

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The ALR for these conditions is between 0.55 and

13.27 m/s for air and 2.72 – 6.53 m/s for water.

which correspond to superficial velocities of 2.95 –

to 3 kg/min and water flow from 76 to 182 kg/min,

experimental conditions. The air flow ranged from 1

and Dukler [8] was used as reference to select the

flow regimes in horizontal gas-liquid flow by Taitel

in the nozzle patent [6]. The model for predicting

liquid mass ratios (ALR) covering the range outlined

bubble, intermittent, and transition flow, with air to

order to have operating conditions in the dispersed

Figure 1. Schematic of the set-up to evaluate the
(a) standard pipe, and (b) configuration with abrupt
changes in the conduit inner diameter. Dimensions
shown in cm.

resolution of 0.0207 and 0.0276 kPa, respectively.
Static pressure measurements were also performed
using the transducer Omega model PX605-300GI
(S1, S2 and S3 in Figure 1), with a range of 0 to
2068 kPa, an accuracy of 0.4 % full scale, and a re-
sponse time of 5 ms.

A preliminary spectral analysis of the pressure
fluctuation signal showed that its dominant fre-
cquency range is below 100 Hz. However, it was of
interest to compare the signals recorded along the
pipe, and as the time lag for these signals is be-
tween -10 and 10 ms, a resolution of 0.5 ms to mea-
sure the time delay was chosen, which corresponds
to a sampling frequency of 2000 Hz. For each op-
erating condition, the signals from the piezoelectric
pressure transducers were simultaneously recorded
at 2000 Hz with a sampling time of 50 s. Analog-
sously, the pressure signals from the static pressure
transducers were simultaneously acquired at 200 Hz
for 10 s.

Air and water were used as testing fluids during
the experiments. The flow rates were selected in
order to have operating conditions in the dispersed
bubble, intermittent, and transition flow, with air to
liquid mass ratios (ALR) covering the range outlined
in the nozzle patent [6]. The model for predicting
flow regimes in horizontal gas-liquid flow by Taitel
and Dukler [8] was used as reference to select the
experimental conditions. The air flow ranged from 1
to 3 kg/min and water flow from 76 to 182 kg/min,
which correspond to superficial velocities of 2.95 –
13.27 m/s for air and 2.72 – 6.53 m/s for water.
The ALR for these conditions is between 0.55 and
3.96%, while the homogeneous void fraction is in
the range of 0.31 to 0.81.

Qualitative evaluation of spray stability

Qualitative evaluation of the spray stability was
performed by direct observation of the spray and
through regular-speed and high-speed videos. When
observing the spray during the experiments for a sta-
ble condition the edges of the spray do not fluctuate,
whereas for an unstable spray its boundaries bounce
and a low frequency and audible sound appear. For
a condition in the transition, the borders of the
jet present slight fluctuations. Regular-speed videos
were recorded using a Canon PowerShot S410 digital
camera which can take videos at 15 frames per sec-
ond (fps) with a resolution of 320x240 pixels. These
videos were recorded from a distance that allowed
the observation of approximately 24 cm of the spray
from the nozzle exit, and were performed at three
operating conditions: 75.7, 113.6, and 151.4 kg/min
of water and 2 kg/min of air. These videos allowed
the validation of previous qualitative evaluations.
High-speed videos were recorded using a Fastcam-
X 1280PCI high-speed, digital, monochrome cam-
era. Videos were taken at 4000 fps for approxi-
mately 0.6 s, at the spray (close to the tip of the
nozzle) and at a short (10 cm) transparent section
of pipe just upstream the nozzle, and were synchro-
nized with the pressure fluctuation signal. An Auri
Sun 1200 W HMI light source was positioned oppo-
site to the camera for the videos of the sprays, while
front lighting was preferred to observe the flow struc-
ture within the transparent pipe. These videos were
recorded at certain operating conditions of interest.
They were analyzed using Photron Motion Tools™,
and were very useful to observe the differences in
the flow structure entering the nozzle, and the spray pat-
tern, for unstable and stable conditions, as well as
in helping understand the relationship between the
pressure fluctuation signal and spray stability.

Pressure fluctuations and spray stability

Description of the pressure fluctuations

Figure 2 depicts the pressure fluctuation signal
for a stable condition with images of the spray at
different instants of the signal, using the standard
configuration. The spray is observed to be uniform
without important changes in time and space.

Figure 3 illustrates the pressure fluctuation for
an unstable condition correlated with images of the
spray and flow entering the nozzle for the standard
configuration. When compared to the stable case,
the signal for the unstable condition has higher mag-
nitude with a definite shape and a fairly constant fre-
quency. The spray presents zones of good dispersion
followed by zones with slugs of liquids, ligaments and
big droplets, while the flow entering the nozzle has
zones of liquid filling the pipe cross-section followed by zones with important amounts of gas. In addition, some sections of each cycle of the signal were found to always be related to certain pattern in the two-phase flow and spray.

This preliminary characterization of the signals does not offer information regarding the phenomena originating the fluctuations in the pressure. In this regard, further analysis was performed using the cross-correlation between the signals recorded along the pipe.

Pressure fluctuations signal processing

The aim when defining the technique to analyze the pressure fluctuations is to propose a simple and effective method to diagnose the spray stability and make a proper comparison between the standard configuration and the alternative with abrupt changes in the conduit inner diameter. The analysis of the pressure fluctuations followed is based on spectral analysis techniques. In addition, the cross-correlation function is used to analyze the relation between the pressure fluctuation signals recorded along the conduit. The pressure fluctuation signals and qualitative results for the standard configuration are used to illustrate the analysis.

Cross-correlation analysis

The cross-correlation function of pressure fluctuations signals has been used by several authors to determine certain characteristics of interest in the systems that they have studied. For instance, Knapper and House [9] used it in the stability analysis of a spray issued from a nozzle assembly as the one used in this study. The cross-correlation is performed here to analyze the relation between the signals recorded along the pipe and, if possible, identify the sources that generate the pressure fluctuations and the direction followed by these signals during their propagation.

The cross-correlation function (CCF) for two time series $x(t)$ and $y(t)$, is given by

$$R_{xy}(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{0}^{T} x(t)y(t+\tau)dt$$

for negative values of $\tau$, the relation $R_{xy}(-\tau) = R_{yx}(\tau)$ is used to compute the CCF. In the normalized form of the CCF, the maximum value of one is reached when $x(t)$ and $y(t)$ are completely overlapped for a given $\tau$.

Table 1 presents, for a stable and an unstable condition, the magnitude of the maximum normalized cross-correlation and the corresponding lag time for $R_{31}$, $R_{32}$ and $R_{21}$, where 3 corresponds to the signal recorded after the mixing device, 2 is that sampled at the middle of the pipe and 1 is the one just before the nozzle.

For the unstable condition the value of the maximum cross-correlation is close to its limit value of one. In addition, for the unstable case the time delay between the signals was found to be negative, indicating that the pressure fluctuations are prop-
Table 1. Cross-correlation and lag time for a stable and an unstable condition.

<table>
<thead>
<tr>
<th></th>
<th>Max. $R_{xy}$</th>
<th>Lag time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable</td>
<td>0.31</td>
<td>8.5</td>
</tr>
<tr>
<td>Unstable</td>
<td>0.365</td>
<td>-5.5</td>
</tr>
</tbody>
</table>

agated in the upstream direction. Since the signal propagates in the upstream direction, it can be inferred that the fluctuations in the pressure for unstable conditions are not mainly caused by the local fluctuations of the two-phase mixture flowing in the downstream direction. The estimated average propagation velocity between the measuring points 2 and 1 is 133.3 m/s. This velocity is very high and can be associated to the sound velocity. Accordingly, it is suggested that the pressure fluctuations signals in the unstable case are fast-propagating pressure waves generated by some of the processes occurring in the nozzle (coalescence and/or eruption of bubbles).

For the stable condition the magnitude of the maximum cross-correlation is smaller than in the unstable case. The lag time was found to be positive, suggesting that the signal is propagated in the downstream direction. However, it must be considered that the cross-correlation is lower in this case, what makes difficult to draw conclusions about the origin and the traveling direction of the signals. The velocity of propagation of the pressure fluctuations in this case is also high. It is suggested that for the stable case the pressure fluctuation at each measuring point is a combination of some of the phenomena occurring in the mixing device (which gives the maximum cross-correlation and positive lag time) and the local fluctuations and sources from other sections of the system.

In summary, the cross-correlation between the signals is small with positive lag time for stable conditions, and increases as the stability decreases having a high cross-correlation and negative lag time for unstable conditions. This was also observed by Knapper and House [9]. This type of analysis is effective to identify characteristics of the signals and their direction of propagation for different stability conditions, however, it does not offer clear indication of where the stability transition occurs, and does not allow comparison between different configurations in terms of the strength of the pulsations.

Spectral analysis

The power spectral density (PSD) corresponds to the distribution of the mean square value of the data over the frequency domain. The PSD for a time series $x(t)$ is defined as:

$$PSD = \int_{-\infty}^{\infty} R_{xx}(\tau)e^{-j2\pi\omega\tau}d\tau$$

where $R_{xx}$ is the autocorrelation of $x(t)$, and represents a special case of the cross-correlation with $y(t) = x(t)$. The area underneath the PSD represents the mean square value of the time series, i.e., the variance plus the square of the mean. Hence, the area beneath the PSD within a frequency range gives an indication of the mean square value of the time series for the specified range.

The PSD of the pressure fluctuation signals was estimated dividing 65536 points of the series into 8 sections, using an overlapping of 50% and a Hannin windowing. A representation of the PSD for a stable and an unstable condition is shown in Figure 4. The unstable case presents a dominant peak at 7.8 Hz. The presence of this peak is an indication of the periodicity of the signal for this condition.
Contrarily, for the stable case no dominant peak is observed and the power is distributed over a broad range of frequencies (5 - 20 Hz). This suggests that the signal is non-periodic and that its frequency is probably changing with time. However, when comparing the two PSD it is evident that its magnitude is much higher for the unstable case. Note that the scale in the independent axis is 200 times higher for the unstable case.

Figure 5. Area beneath the PSD ($f \leq 40$ Hz) of the pressure fluctuations as function of the liquid superficial velocity for the standard feeding pipe.

The quantification of the information contained in the PSD was achieved by evaluating the energy contained within the frequency range of 0–40 Hz, which is equivalent to calculate the area beneath the PSD for that range of frequencies. Figure 5 shows the trends of the area beneath the PSD for different air flow rates as function of liquid superficial velocity. The low values (flat portion) correspond to stable conditions and are associated with higher liquid flow rates. As the spray becomes unstable, for a given air flow, the area beneath the PSD is seen to increase substantially. The breakpoints in the curves correlates very well with the conditions at which the transition from stable to unstable was observed during the experiments. The same type of performance is observed when using the mean square value of the signal; however, the area beneath the PSD for the frequency range considered presents a more abrupt change in the slope of the trend when the conditions pass from stable to unstable, which eases the identification of the stability transition.

Results and Discussion

Figure 6 presents a flow map with the operating points evaluated and the corresponding stability condition obtained using the breakpoints presented by the area beneath the PSD for frequencies below 40 Hz. The superficial velocity of the conditions plotted in this map were calculated using the mean pressure measured just upstream the nozzle, consequently, the conditions correspond to the flow entering the nozzle. The flow regime transition based on the model by Taitel and Dukler [8] is superimposed on this flow map. It must be noted that this transition depends on the operating pressure [8], thus, a combination of the transitions calculated for 500, 1000, and 1500 kPa was chosen as reference. It is observed a good correlation between the stability conditions and flow pattern entering the nozzle, this is, a stable spray is obtained for dispersed bubble flow in the feeding pipe, while unstable sprays correspond to intermittent flow entering the nozzle. This confirms the effect that the two-phase flow pattern has on the stability of the spray.

Figure 6. Flow map of the operating points with their corresponding stability condition for the standard feeding pipe. The dispersed bubble transition by Taitel and Dukler [8] is superimposed on this map.

Figure 7 depicts the trends of the area beneath the PSD for the alternative with abrupt changes in the inner diameter of the pipe as a function of the liquid superficial velocity. As in the standard case, these trends present well-defined break points changes in the slope for each air flow, which correspond to where the transition between stable and unstable conditions was qualitatively observed. Figure 8 depicts a flow map for the alternative with abrupt changes in the conduit diameter. There is an evident improvement in the stability range, as lower liquid flow rates can be handled before the onset of unstable conditions. Based on the stability transitions observed in Figure 6 and Figure 8 an ac-
ceptable decrease of water flow, while maintaining stable conditions, was determined to be 15 kg/min for the lower gas flow and 40 kg/min for the higher gas flow.

![Figure 7. Area beneath the PSD (f ≤ 40 Hz) of the pressure fluctuations as function of the liquid superficial velocity for the alternative with abrupt changes in the inner diameter of the pipe.](image)

A parameter based on the area beneath the PSD of the pressure fluctuations for frequencies below 40 Hz enables determination of the stability condition of the gas-liquid spray and shows where the stability transition is. In addition, it allows comparisons between the standard configuration and the proposed modification to the feeding pipe.

![Figure 8. Flow map of the operating points with their corresponding stability condition, for the alternative with abrupt changes in the inner diameter of the pipe. The dispersed bubble transition by Taitel and Dukler [8] is superimposed on this map.](image)

The dispersed bubble transition by Taitel and Dukler [8] is superimposed on this map.

The increase in the range of stability and the decrease of the pulsation strength was qualitatively confirmed during the experiments. In addition, the increment in the pressure drop was found to be small when compared to the operating pressure (< 2.2%), and ranged between 3 and 25 kPa over the pressure drop for the standard case.

**Conclusions**

- A parameter based on the area beneath the PSD of the pressure fluctuations for frequencies below 40 Hz enables determination of the stability condition of the gas-liquid spray and shows where the stability transition is. In addition, it allows comparisons between the standard configuration and the proposed modification to the feeding pipe.

- Using a series of abrupt changes in the inner diameter of the feeding pipe offers an important improvement to the range of stability of the gas-liquid spray. A decrease of around 15–40 kg/min of water can be achieved for a constant air flow before the onset of unstable conditions.

- The analysis of pressure fluctuations requires a good understanding of what generates the fluctuations in the pressure, and their relation with the characteristics of the system.
Acknowledgement

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Nomenclature

\begin{itemize}
\item $D$ pipe diameter, m
\item $L$ pipe length, m
\item $U$ velocity, m/s
\item $R$ cross-correlation
\end{itemize}

Subscripts

\begin{itemize}
\item $GS$ gas superficial
\item $LS$ liquid superficial
\end{itemize}

References


