Acoustic Detection of Flooding in Absorption Columns and Trickle Beds

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Abstract

In countercurrent flow absorption columns and trickle beds, if either the liquid or gas flow is too high the column becomes flooded with the liquid. Flooding is accompanied by a dramatic increase in pressure, resulting in inefficient operation and potential damage to equipment. To optimize efficiency, however, it is desirable to operate as close to flooding as possible. This article discusses the feasibility of using acoustic emissions for an non-intrusive, in situ method of monitoring column operations. Six piezoelectric microphones were placed on the outside of a packed column and acoustic signals between 0 Hz and 20 000 Hz were acquired over conditions ranging from non-flooded to flooded. The raw signals were then processed to obtain their standard deviation and entropy. Standard deviation and entropy were both found to increase at the onset of flooding. Entropy, however, was more useful because it was not sensitive to the type of packing, air flow rate or water flow rate. Additionally, entropy began to increase sooner than standard deviation, providing an early warning. The results from both entropy and standard deviation proved acoustic detection can be used non-intrusively to monitor operations, allowing for better optimization and improved efficiency of absorption.

Keywords: acoustic emissions, acoustic monitoring, flooding, absorption columns, trickle beds

1. Introduction

1.1. Absorption Columns and Trickle Beds

An absorption column is a packed column with a gas inlet at the bottom and a liquid inlet at the top. The countercurrent flow of the two fluids allows for the mass transfer operation known as absorption, where a component of the gas mixture is transferred to the liquid phase in which it is soluble [1]. Some common applications include, removing pollutants from plant emissions, purifying natural gas and recovering carbon monoxide in petrochemical production [2].

Trickle beds are also used in absorption operations. The beds are composed of catalyst pellets, rather than ordinary packing and fluid flow can be either co-current or countercurrent [3]. Some common applications using countercurrent flow include catalytic distillation, hydrodesulfurization and ultra clean diesel fuel production [4].

1.2. Flooding

Flooding occurs when either the vapour or liquid flow is increased beyond the capacity of the column. In countercurrent operations, the gas inhibits the liquid flow and increased friction between the two fluids causes the liquid to backup [5]. The accumulation of liquid at the top of the packing acts as a visual indication of flooding.

Flooding is also accompanied by a rapid increase in pressure drop and liquid holdup [6]. The rapid increase in pressure drop and decrease in flow efficiency upon flooding makes the system inoperable [7]. The efficiency of interfacial mass transfer, however, is maximized near the flooding point [8]. Therefore, it is desirable to operate as close to flooding as possible, without actually reaching flooding and causing instability. Reliable online detection of flooding would make it possible to operate at optimal mass transfer conditions.

1.3. Flooding Detection

Different methods have been used to detect flooding, including visual detection, measuring liquid holdup and monitoring pressure.

If the column being used is transparent, the “visual buildup of liquid on the upper surface of the packed bed,” as described by Strigle [6], can be observed. The problem with visual observation is that there is often a delay in reaction and by the time flooding is noticed damage or loss has already taken place. In addition, hysteresis effects have been observed to delay column recovery by Celata et al. [9] and Shoukri [10]. With hysteresis, flooding persists until the flow rate is reduced to a level much lower than the critical flow rate [9], making restoration of normal column operation more difficult.

Flooding can also be identified by an increase in liquid holdup in the column. To measure liquid holdup, both gas and liquid flows must be stopped and the liquid remaining in the column must be drained [6]. Thus, using liquid holdup as an indicator of flooding disrupts operations and cannot be monitored online.

As flooding is accompanied by a dramatic increase in pressure, monitoring the pressure drop in a column or bed using sensors is a potential online method of flooding detection. It is not clear however, whether pressure sensors are capable of detecting flooding onset or simply flooding. In addition, monitoring pressure requires intrusive alterations to equipment in order to properly position sensors.

1.4. Acoustic Detection

This research discusses the feasibility of using microphones as an inexpensive, non-intrusive, online method of detecting flooding onset. Piezoelectric microphones were attached to the outside of a packed column to monitor operations. Sound waves, which are simply propagations of pressure imbalances through fluid media, deformed the piezoelectric material generating a voltage signal [11]. The voltage signal could then be processed and analyzed using various statistical analysis techniques.

1.5. Signal Analysis

Several different types of advanced signal analysis were performed on the raw data obtained from the piezoelectric sensors. Standard deviation and entropy yielded the simplest and most informative results.

The standard deviation represents the fluctuations in a signal away from the mean [12]:

$$s_N = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2} \qquad (1)$$

where, N is the sample size, x_i is a single value from the sample data and $\bar{x}$ is the mean of the sample data [13].

Entropy, in the context of information theory, is a measure of the information contained in a signal or event. The absence of information represents an uncertainty associated with the event; this uncertainty is known as the entropy of information or Shannon's entropy [14]. The entropy of information, H, for an event, X, was defined by Claude E. Shannon as follows [15]:

$$H(X) = -\sum_{x} P(x)\log_2\left[P(x)\right] \qquad (2)$$

Where $P(x)$ is probability of an outcome, x, for the event, X. Therefore, the entropy of information is the negative summation of the probability of each possible outcome multiplied by its base 2 logarithm.

2. Apparatus and Procedure

2.1. Apparatus

The apparatus consisted of a clear, acrylic absorption column with a diameter of 0.10 m and a height of 1.46 m (Fig. 1). The water inlet was at the top and the gas inlet was at the bottom. A metal perforated plate separated the bottom of the column from the downcomer.

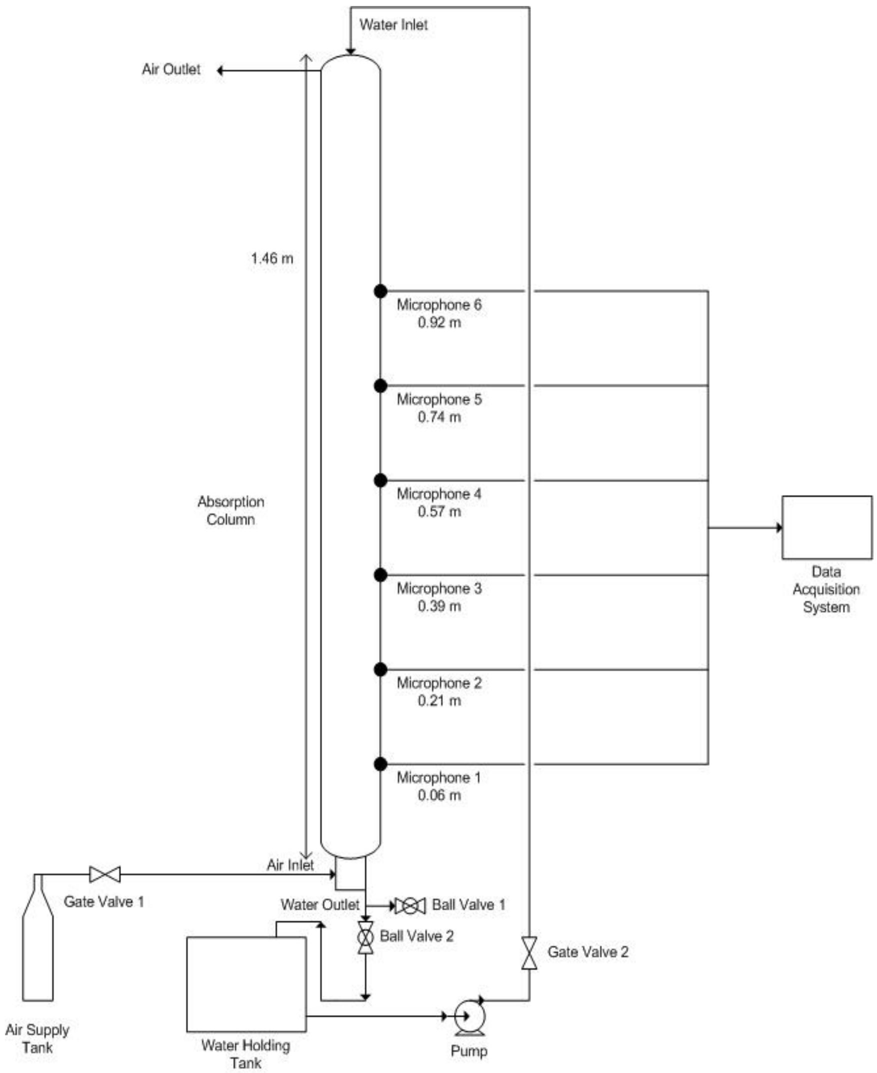

Figure 1: Experimental apparatus

Water was supplied from a 0.13 m^3 holding tank using a SHURflow pump. Air was supplied from compressed air lines in the laboratory. Two gate valves permitted the control of water and air flow. Two ball valves were connected to the water outlet pipe to enable liquid holdup measurements.

Six microphones, manufactured by Piezotronics Inc., were securely placed on the exterior surface of the column using metal microphone holders and Velcro straps. The microphones were connected to signal conditioners, which fed into a National Instruments data acquisition system connected to a Dell Inspiron laptop.

Three different types of packing were used in the column: 13 mm ceramic Raschig rings, 13 mm ceramic Intalox saddles and 13 mm glass marbles.

2.2. Procedure

In all cases, the absorption column was operated at a constant air flow rate while the water flow rate was increased in 0.5 LPM increments. Microphones feeding into a data acquisition system were used to acquire acoustic signals for 60 s at 40 000 Hz, for each combination of air and water flow rates. Data was acquired both prior to and during flooding, for air flow rates of 40 LPM, 50 LPM, 60 LPM, 70 LPM and 80 LPM. In addition, it was noted when flooding could be visually observed in the column.

To acquire liquid holdup measurements, liquid flow through the column was stopped using ball valve 2 (Fig. 1). Ball valve 1 was then opened and the water held in the column was collected in a bucket and weighed.

Pressure differential readings were taken using an Omega Engineering Inc. pressure transducer connected at the top and bottom of the column.

3. Experimental Results and Discussion

3.1. Visual Observations

Due to the transparent nature of the column, flooding could be visually observed. With the Raschig rings and Intalox saddles, flooding could be identified during onset at the base of the packing. Flooding onset was difficult to detect with the marbles and was not noticed until the liquid accumulated on top of the packing.

3.2. Pressure Differential

The pressure differential was found to be an ineffective method of detecting flooding, likely because of the equipment setup. Accurate measurements require differential pressure transducers, which must be connected to two different locations on the column wall. Any liquid entering the lines will falsify the measured pressure differential. While this can be avoided by measuring the pressure difference between the gas inlet and outlet, the distributor pressure drop is then included in the measured pressure differential. Including the pressure drop across the distributor was found to overshadow the actual bed pressure drop, making flooding difficult to identify.

3.3. Liquid Holdup

Measuring the operating liquid holdup proved to be an effective method of identifying flooding for all three types of packing at all five air flow rates. Fig. 2 shows the operating liquid holdup for Raschig rings at a 70 LPM air flow. The flooding point was identified as the intersection of the two lines linearly fit through the data. In this case, the flooding point was 5.0 LPM.

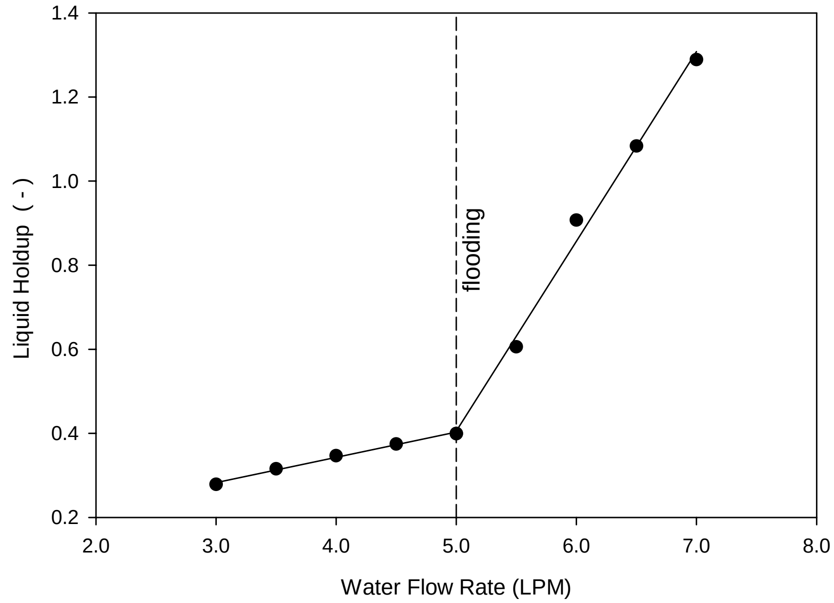

Figure 2: Liquid holdup versus water flow rate at 70 LPM air flow with Raschig ring packing

Although effective at identifying flooding, stopping liquid flow and draining the liquid from the column to measure holdup was disruptive to operations. Thus, an online method of flooding detection is preferable.

3.4. Acoustic Detection

In both the standard deviation and entropy analyses, all six microphones were able to detect a change at flooding. Therefore, only one microphone was actually necessary to monitor operations.

Plots of standard deviation were generated for each of the three types of packing, at air flow rates of 40 LPM, 50 LPM, 60 LPM, 70 LPM and 80 LPM. An example is shown in Fig. 3, for Raschig rings at an air flow rate of 70 LPM. A sudden increase in standard deviation can be visually observed at 5.0 LPM water flow, as indicated by the vertical line; this matches the flooding point found using the liquid holdup technique, under the same experimental conditions.

The plots for all three types of packing showed similar increases in standard deviation at the onset of flooding. Microphone 5 always appeared significantly above the rest, because it was positioned closest to the top of the packing. Upon flooding the packing at the top would rattle, producing sound waves that were strongest near this microphone. In the rest of this article, results are presented only for microphone 1, positioned at the bottom of the column.

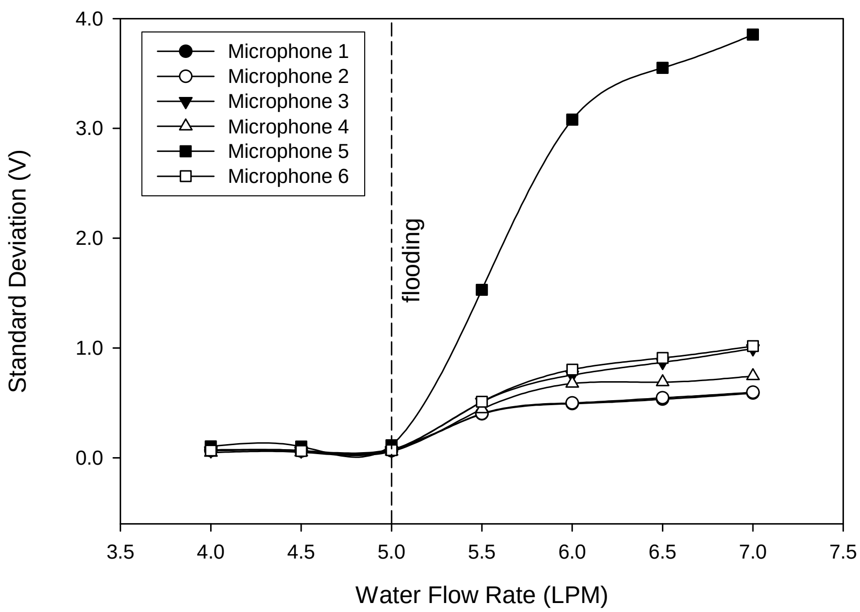

Figure 3: Standard deviation versus water flow rate at 70 LPM air flow with Raschig ring packing

The increase in standard deviation with flooding was expected. At flooding there was an audible increase in noise. The increase in noise corresponds to an increase in pressure fluctuations, which would have been detected by the microphones. Larger pressure fluctuations produce larger signal fluctuations about an average, thereby resulting in a higher standard deviation.

A threshold was identified at flooding onset for each type of packing. The rings, saddles and marbles were found to flood at standard deviations of 0.10, 0.17 and 0.15 V respectively. Fig. 4

illustrates the application of the threshold to the previous standard deviation plot for Raschig rings at an air flow rate of 70 LPM, for microphone one only.

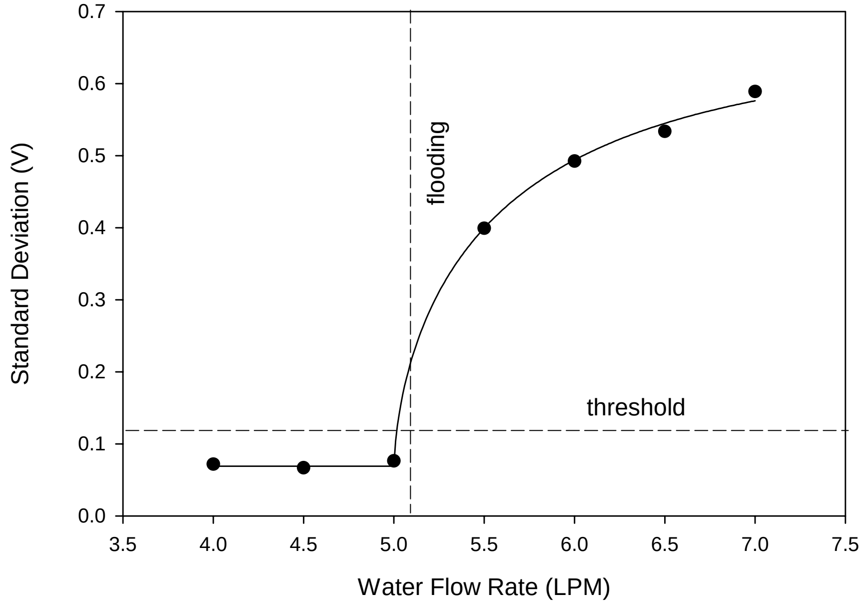

Figure 4: Threshold for standard deviation versus water flow rate at 70 LPM air flow with Raschig ring packing

The standard deviation technique was validated by comparing its results with results from the proven liquid holdup method. First, the water flow rates at flooding were found by interpolating at the respective standard deviation threshold, for each combination of liquid and gas flow rates. The standard deviation flooding points were then plotted against those found using the liquid holdup technique, for all types of packing (Fig. 5). The linear relationship between the flooding points demonstrates that standard deviation is a valid method for identifying flooding for all three types of packing and every combination of liquid and gas flows. Standard deviation can be measured online without disrupting operations and is therefore a preferable method to measuring liquid holdup.

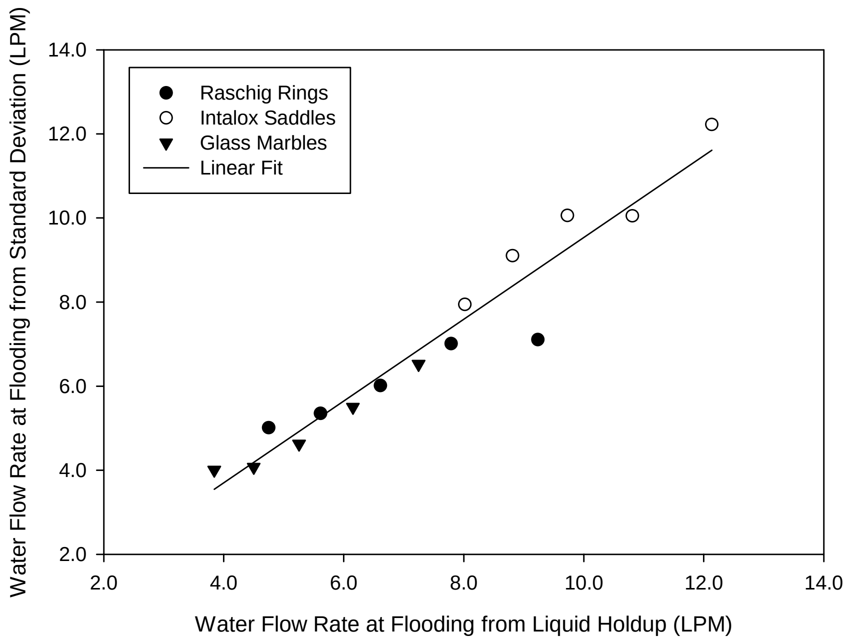

Figure 5: Correlation between flooding water flow rates obtained from the standard deviation of the microphone signal and the liquid holdup

One drawback to using standard deviation is that the flooding threshold is not independent of packing type. Another disadvantage is standard deviation does not detect flooding before it occurs. An early warning is more desirable, because adjustments can be made before flooding begins, minimizing potential damage and lost operating time. A second signal analysis technique, entropy, however was found to give an early warning.

Entropy was plotted for all three types of packing, at all five air flow rates. Fig. 6 shows the entropy for Raschig rings at an air flow rate of 50 LPM. Two distinct plateaus were observed on either side of the vertical line. The vertical line represents the water flow rate where flooding was identified using the liquid holdup method. Therefore, the first plateau corresponds to non-flooding conditions while the second corresponds to flooding conditions. The area between the two plateaus represents a transition region between the two flow conditions.

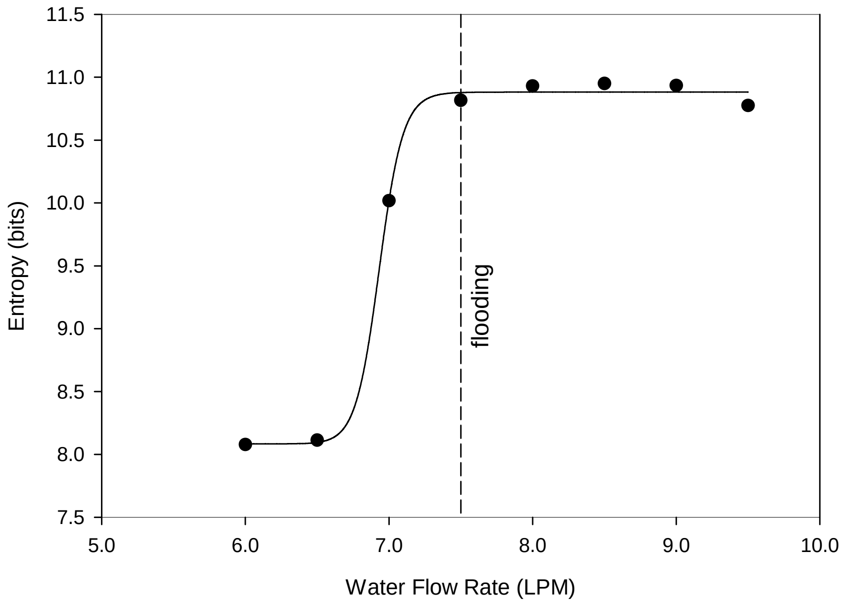

Figure 6: Correlation between flooding water flow rates obtained from the standard deviation of the microphone signal and the liquid holdup

The increase in entropy with flooding was expected. When the column flooded it became unstable and consequently the information detected by the microphones was less certain. This greater degree of uncertainty led to higher entropy values. Overall, entropy started at an average of 8.6 bits and rose to an average of 10.5 bits at flooding.

The entropy technique was validated the same way as standard deviation, by comparing all the flooding points found to those identified using the liquid holdup method. The linear relationship between the flooding points, as shown in Fig. 7, demonstrates that entropy is also a valid method for detecting flooding. The entropy of the microphone signal accurately predicted flooding for all three types of packing, at every combination of liquid and gas flow rates. Like standard deviation, entropy is superior to liquid holdup, because it can be measured online without interrupting normal operations. Entropy, however, is also superior to standard deviation. The first reason entropy is superior, is the transition region. The transition region is the gradual increase in entropy between the two plateaus (Fig. 6). The increase begins before the liquid holdup flooding point and therefore acts as an early warning.

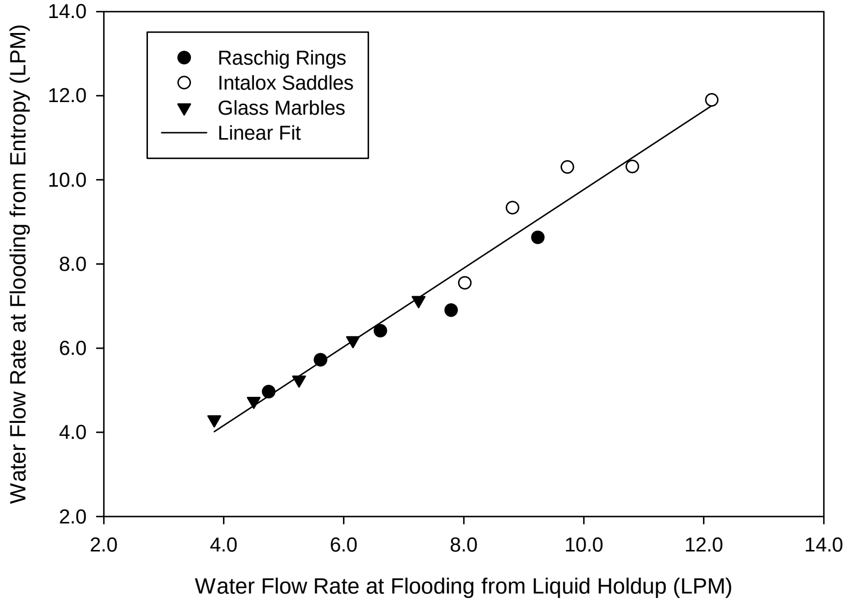

Figure 7: Correlation between flooding water flow rates obtained from the entropy of the microphone signal and the liquid holdup

Fig. 8 confirms the transition region exists in the same location for each type of packing, at every combination of air and water flow rates tested. It contains data from all the individual entropy plots, similar to the one in Fig. 6. The points were classified as not flooding, transition, or flooding and combined on a single plot.

In Fig. 8, three distinct regions are visible. The first region lies below an entropy value of 9.1 bits and encompasses data prior flooding. The second region is the transition region, contained between 9.1 bits and 9.8 bits. The final region represents flooding and includes all data above 9.8 bits. As the same transition boundaries applied to all cases, it can be concluded that entropy is independent of packing type, air flow rate and water flow rate. This independence is the second reason entropy is superior to standard deviation, as it presents an opportunity to develop an entropy threshold for a given column that will not change with the type of packing, air flow rate or water flow rate.

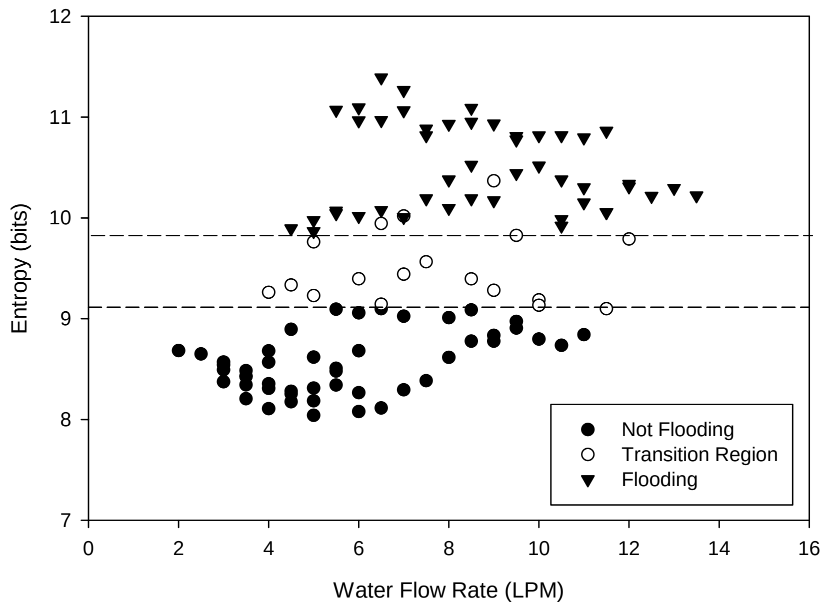

Figure 8: Summary of entropy versus water flow rate

Setting an entropy threshold in the transition region would allow adjustments to be made to prevent flooding before it occurs. For example, setting the entropy threshold at 9.1 bits was found to predict a liquid flow rate 5% below the critical liquid flow rate, leaving a sufficient window for adjustments before flooding onset. Fig. 9 demonstrates the threshold in relation to the flooding point for Raschig rings at an air flow rate of 50 LPM. The threshold lies in the transition region sufficiently before the actual flooding point. The threshold of 9.1 bits also holds for the two other packings at all air and water flow rates tested.

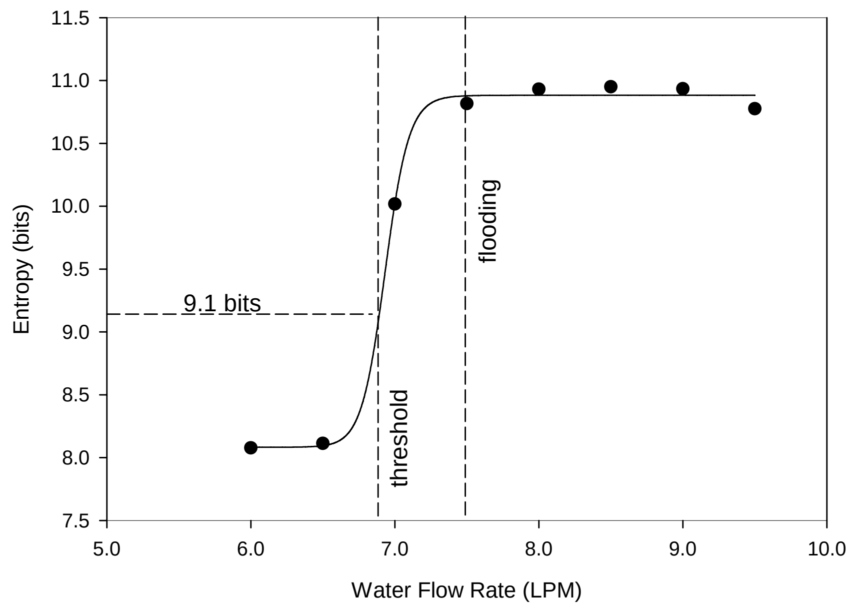

Figure 9: Entropy versus water flow rate at 50 LPM with Raschig ring packing and a threshold

Fig. 10 validates the threshold by relating the water flow rate 5% below flooding, as determined from the entropy of the microphone signal, to the water flow rate 5% below flooding, as determined from the liquid holdup, for all cases. The linear relationship proves that in addition to entropy being a strong predictor of flooding it is also able to predict the flow rate 5% below onset. As a result, a threshold of 9.1 bits is a valid warning signal for flooding. Early warning is critical to preventing equipment damage and operating delays that may result from flooding. Thus, online monitoring of the entropy within a system could be of great value to industries that utilize absorption.

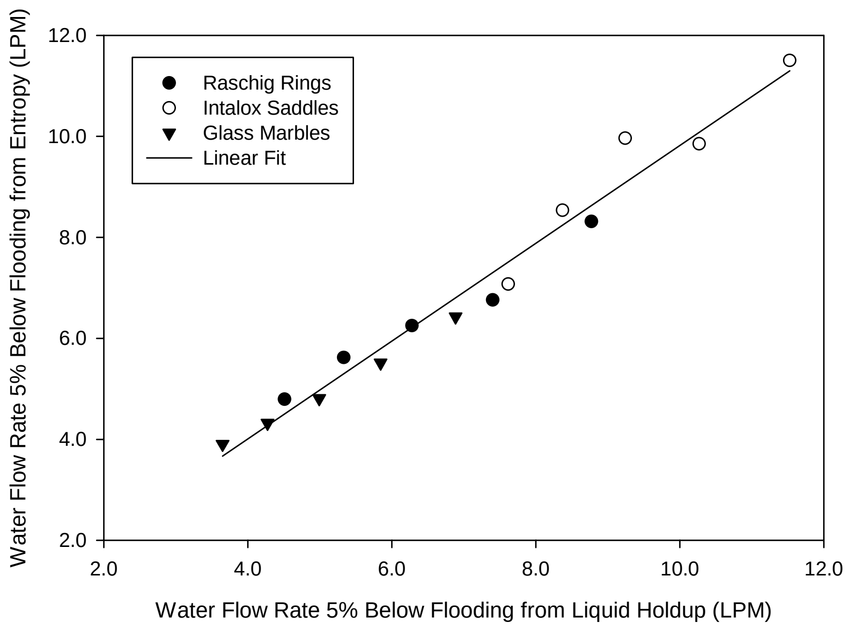

Figure 10: Correlation between critical water flow rates obtained from the entropy of the microphone signal and liquid holdup

4. Conclusions

Acoustic detection using piezoelectric microphones placed on the outside of the column wall is an effective method to detect the onset of flooding. Both standard deviation and entropy increased sharply with flooding onset. Visual observations and liquid holdup measurements confirmed that flooding was correctly identified using acoustic techniques.

Any one of the six microphones was able to detect flooding. A microphone at the bottom of the column is recommended for the earliest detection.

Although standard deviation clearly indicated the onset of flooding, entropy is the preferred method of detection. Entropy was shown to be independent of the type of packing, air flow rate and water flow rate and thus it is a more robust and general indicator. Additionally, entropy provides an early warning and the opportunity for user intervention before flooding occurs.

The non-intrusive nature of this acoustic detection method would prove useful in industry, allowing companies to more accurately monitor operations and enabling safe operation closer to flooding to maximize mass transfer efficiency.

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Nomenclature

H	entropy, bits
N	sample size, dimensionless
$P(x)$	probability of outcome x, dimensionless
s_N	standard deviation, measurement units
x	outcome, measurement units
X	event, dimensionless
x_i	data value, measurement units
$\bar{x}$	mean of sample data, measurement units