Towards Online Characterization of Oxygen Delignification in Kraft Pulping

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ABSTRACT

Being able to monitor the size of gas bubbles would be useful, because this property is known to be one of the most important factors affecting the performance of several industrial processes designed for separating solids from liquids and for facilitating heat and mass transfer between separate phases. In this paper, a novel methodology for automated characterization of oxygen dispersion bubbles is presented. The approach is based on analyzing digital images produced by an industrial CMOS camera which is attached to the process by a borescope. The developed methodology for analyzing images offers robustness and fastness which are significant advantages when it comes to online use of the method in real-life industrial environments. The approach is demonstrated in an oxygen delignification process, which is an important stage of chemical pulping and widely used for lignin removal before pulp bleaching stages. The results show that the method enables online monitoring of oxygen bubble size.

1 INTRODUCTION

Oxygen delignification is an essential stage of chemical pulping and widely used for lignin removal before bleaching pulp /1/. Oxygen is first mixed into medium-consistency fiber suspension with fluidizing mixers to generate as homogenous three-phase dispersion as possible. After the mixing stage, pulp is transferred into oxygen delignification reactor where delignification reactions occur during a flow-through lasting about one hour. Efficient gas-liquid mass transfer is important for oxygen delignification /2/. This is because oxygen diffusion is naturally slow and oxygen is poorly soluble especially at a delignification stage having a high alkali concentration and high temperature, although an increased pressure somewhat increases the solubility.

Mixing of oxygen into medium-consistency pulp is a very energy-intensive unit operation. It is possible that mixer design, its operation and operation of the whole delignification process could be improved if the bubble size distribution of the oxygen gas could be determined. Moreover, it is suggested that factors such as mixer rotor speed and pulp consistency may affect the bubble size in oxygen delignification /3/, so it is presumable that it could be possible to optimize bubble size and thereby achieve a more efficient process, but this necessitates information on the bubble sizes in different conditions. Recent development of camera and illumination technology has made imaging of gas dispersion in oxygen delignification possible, and the development of this kind of imaging method has been described by Mutikainen et. al /4/.

Traditionally, optimization of industrial oxygen delignification systems is demanding, because it requires optimization of reaction chemistry, chemical kinetics, and mass transfer rates /2/. Based on the promising results by Mutikainen et al. /3–4/ it is assumed here that digital image data could provide a useful source of information to be used in the characterization and optimization of the oxygen dispersion process. However, manual analysis of a large number of digital images is not feasible in the long run, because it is time-consuming, laborious, and prone to random and systematic errors. For this reason, algorithms enabling an automatic or semi-automatic processing are particularly useful in characterizing dispersion bubbles /5/. Preferably, the images should be analyzed, not only automatically, but also online to enable efficient monitoring and control of the dispersion process. Such automated online and offline imaging solutions have been presented for the characterization of ash particles /6–7/ and flocculation /8–11/, for example.

In this paper, a novel methodology for automated characterization of oxygen dispersion bubbles is presented. The approach is based on analyzing digital images produced by an industrial CMOS camera.

2 MATERIALS AND METHODS

The imaging system used in this study includes an industrial CMOS camera (Guppy PRO F-503B, 5 megapixels), a borescope, a lighting unit (Cavilux Smart) connected to the borescope by an optical fiber, and a measurement PC (See Figure 1).

Image data were collected from an imaging assembly installed to the oxygen delignification stage of a kraft pulp fiber line. The assembly was placed just before the reactor tower of the 1st oxygen stage. During the mill experiments, the effect of mixer rotor speed to oxygen gas dispersion was being observed. Image data were collected using a frame rate of 3.5 fps during a few minutes for each selected mixer rotor speed (890, 1000, 1100, 1200, 1300 and 1380 rpm).

Collected image data were then analyzed by naked eye to get validation data for image analysis; 10 images from every sampling point were evaluated one by one using a Matlab-based annotating tool.

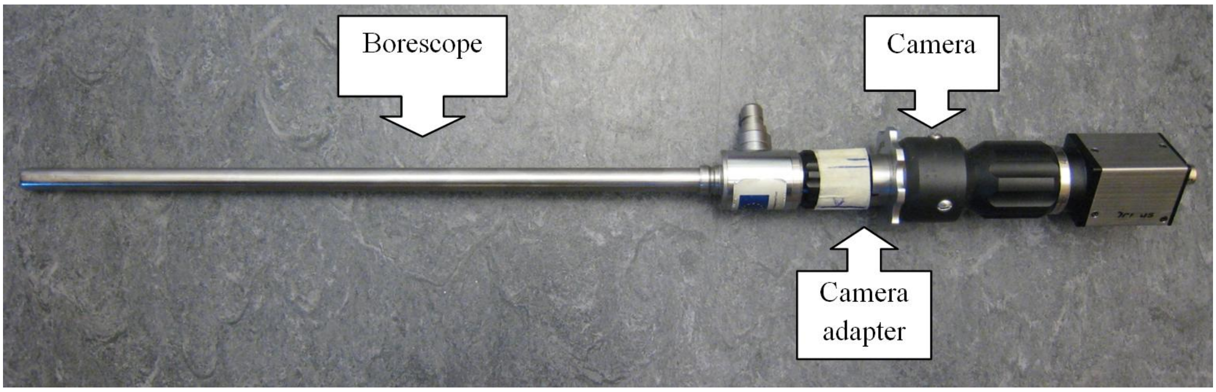

Figure 1. The *in situ* part of the measurement equipment used on the kraft pulp fiber line.

The starting point for designing the image analysis methodology for oxygen bubbles was that it should be, not only able to determine bubble sizes, but also online-applicable, relatively fast, and robust. Looking at the problem from this offset, a novel computational, online applicable methodology for characterizing oxygen dispersion bubbles in digital images was developed. The method involves the following main stages:

1) Pre-processing
2) Binarization and morphological operations
3) Analysis

Original images produced by the camera are extremely challenging in terms of reliable analysis (See Figure 2), for which thorough pre-processing is needed. Pre-processing of bubble images constitutes a 5-stage procedure which includes cropping, taking an image complement, intensity adjustment, 2-D adaptive noise removal filtering, and contrast-limited adaptive histogram equalization.

Binarization can be performed either using an automatically defined or a fixed threshold. The binary image is eventually created using a 4-connected neighborhood.

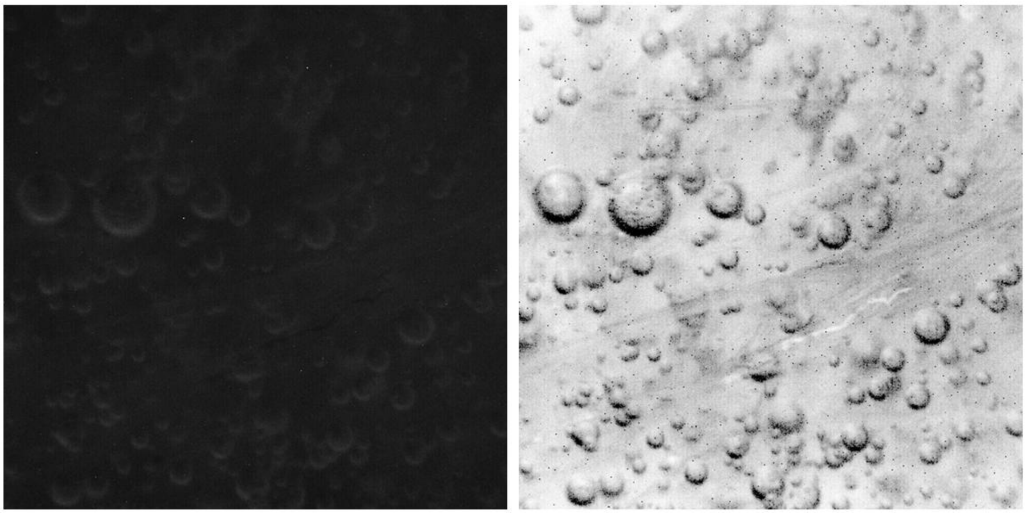

Figure 2. An original (cropped) image on the left, and the same image after intensity adjustment and 2-D noise removal filtering.

Connected components, or objects, can be identified from the binary image using the defined neighborhood. At this stage, as we wish to analyze bubbles assumed to be circular in shape, we are primarily interested in objects having a round form. Therefore, the detected objects can be filtered by their eccentricity, which is the ratio of the distance between the foci of an ellipse surrounding the object and its major axis length. After this, the diameters and volumes of the detected objects can be calculated as pixels and transformed to desired units if the pixel size is known. In this case, the resolution was 1480 pixels per millimeter.

The whole procedure of analyzing a single image takes about four seconds per image on a PC having a double core 1.9 GHz CPU and Windows 8 operating system, which is acceptable in terms of controlling the process.

3 RESULTS AND DISCUSSION

To validate the analysis procedure, the image analysis methodology was applied to the set of images evaluated one by one using the manual procedure. The results gained by the analysis method were compared to those based on manual analysis (See Figure 3). Our results show that the correlation between the computed and manually estimated values is generally good. Overall, the results indicate that it is possible to estimate the size of oxygen bubbles in the delignification process automatically by this approach.

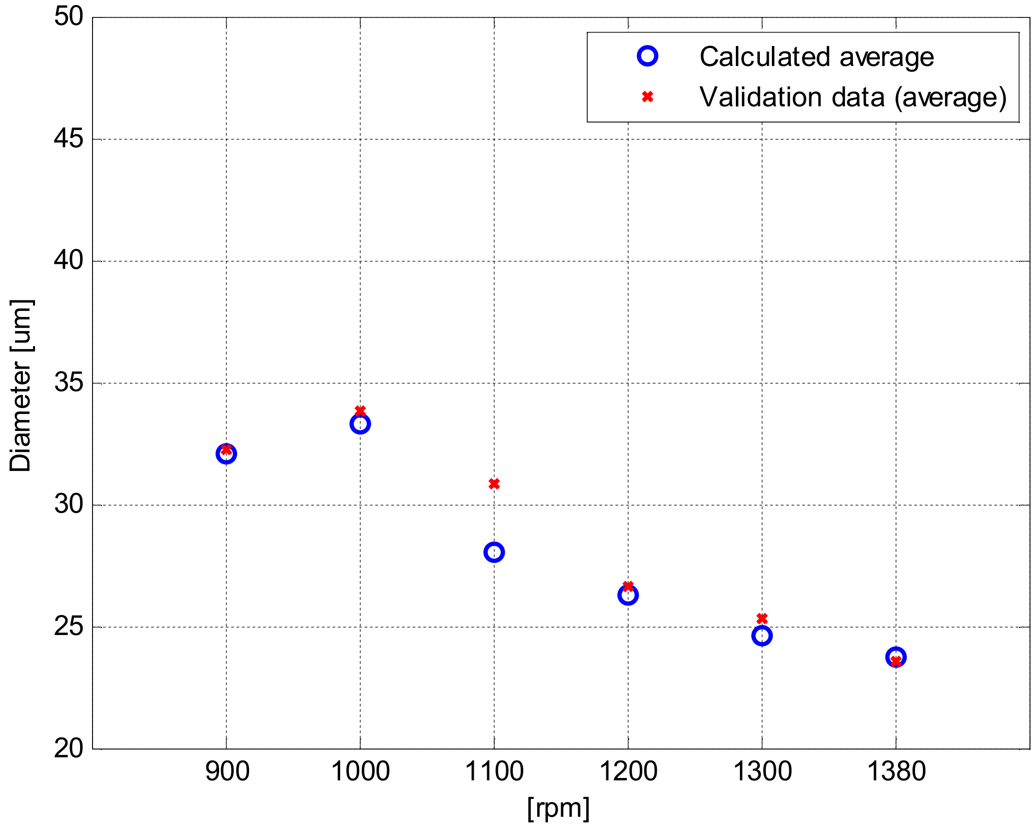

Figure 3. Comparison of averages calculated by the image analysis procedure (automated method) to validation data (manual method)

Based on the results it seems that there is a clear dependence between the mixer rotor speed and bubble size. As a rule of thumb, smaller bubbles enable more homogeneous heat and mass transfer and therefore more efficient separation of solids. To be more exact, using smaller bubbles increases the total surface area for mass transfer, which ensures maximum oxygen concentration in the suspension starting from right after the mixer through the entire oxygen stage.

In this case it seems that increasing the mixer rotor speed produces smaller oxygen bubbles, so the general conclusion would be to increase the mixing rate as high as possible. However, at the moment it remains uncovered what the optimal bubble size would be to achieve optimal delignification with the smallest possible oxygen dose and mixing rate. The tool presented in this paper opens new possibilities to investigate these things.

4 CONCLUSIONS

Based on the results it can be suggested that digital image data are useful in characterizing and optimizing the oxygen delignification process. The advantages of the method are robustness and fastness, which are properties that make the method very suitable for online monitoring in a real process. Furthermore, addition of new information such as oxygen concentration and other process measurements could make it possible to create more exact models, to optimize delignification and to even design a novel advanced control strategy.

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