# Biomass woodchip tracking by image analysis in a model of a fixed bed combustor

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**Abstract.** Energy sector sustainability is one of the main concerns in the recent years. Biomass, in form of woodchips, is interesting for direct combustion in external combustion cycles (e.g. supercritical $CO_2$ Brayton cycles) due to the opportunity of using low quality and low environmental impact fuels. In this study, a direct combustion system working with biomass woodchips is investigated by means of an image analysis technique. The system is made up by a screw conveyor and a fixed bed, where the woodchips are processed. The analysed device operates in cold-condition, and woodchips are partially coloured according to their dimensional class to be traced once these reached the bed surface. A proper algorithm was developed to identify the particles size, define and detect macroparticles centres, and evaluate the main particles motion pattern by comparing the centre positions during time. The results were particularly useful to understand potential inefficiencies of the combustion system due to an uneven woodchips distribution. In addition, the results achieved with the proposed test rig and the adopted methodology can also be used to validate results from Discrete Element Modelling (DEM) simulations.

## 1 Introduction

The use of solid biomass in external combustion cycles is a promising option in order to reduce the greenhouse emissions [1]. It can be applied to several scenarios such as $CO_2$ supercritical cycles or tri-generation systems [2,3], where an externally fired gas turbine (EFGT), an Organic Rankine Cycle (ORC) or an absorption cycle may be used to produce electricity and heat available at different temperatures [4]. The use of solid biomass, such as woodchips, can be suitable for this type of use in direct combustion application. A fuel supply system, usually a screw conveyor, brings the woodchips into a combustion chamber (e.g. a fixed bed) where the hot flue gases are produced. These gases provide heat to the system by means of a proper heat exchanger, while ash and exhaust material are mechanically removed by the bed. Therefore, the woodchips distribution in the combustion chamber is of a great interest to optimize the heat release. Different techniques have been studied in the literature to investigate the woodchips mechanical interactions and their motion inside the reactors. One strategy consists in simulating the mechanical system to obtain the desired data. For instance, Mahmoudi et al. [5] used an Euler–Lagrange approach to simulate the particle motion in a fixed bed with the purpose to enhance the device effectiveness. With their simulations, they were able to properly reproduce the main experimental temperatures and chemical profiles inside the bed. Wiese et al. [6] also pursued a discrete element approach simulation strategy to observe the pellet behaviour in an operating stove. Local effects due to the fuel uneven distribution have been highlighted by the authors.

Direct-observation methods mainly rely on the characterization of the mean residence time of the fuel in the reactors and are based on the adoption of tracers. For instance, Xi et al. [7] investigated the residence time distribution (RTD) of a solid fuel mixer. They released coloured particles in the system and collected them at the end of the process. Lachin et al. [8] studied the RTD in a wheat straw biomass screw-driven pre-treatment device by using a chemical tracer as primary fuel additive. In particular, they used sodium carbonate as a tracer mixed with the biomass, which concentration over the time was determined by measuring the mixture conductivity, thus calculating the RTD of the straw.

In the present work, a direct observation method has been used to quantify the woodchips motion on the surface of a biomass fixed bed combustion system. The fuel is inserted by means of a rotating screw feeder from the bottom of the bed. The experiment is conducted in cold environment, with no combustion occurring. Coloured woodchips were used as tracer and an imaging process method was developed to continuously monitoring the particles behaviour. A proper algorithm was used to follow the macroparticles centres along the time, thus reconstructing the woodchips motion pattern on the fuel bed surface i.e. the most chemically and thermally active part in the combustor. Data shows that the proposed method can provide a continuous monitoring of the woodchips distribution and can also predict the RTD of the fuel.

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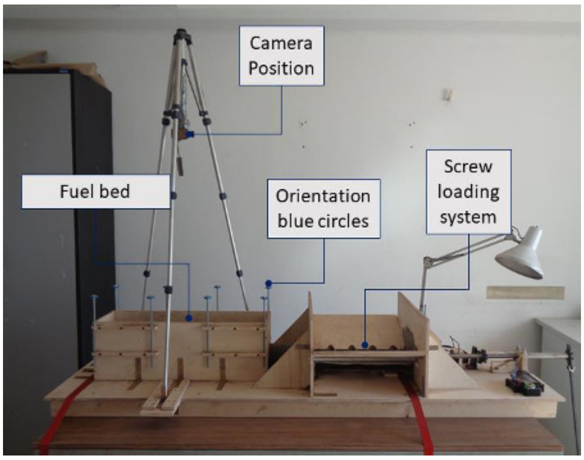
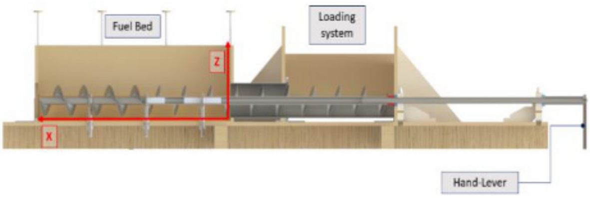
## 2 Method

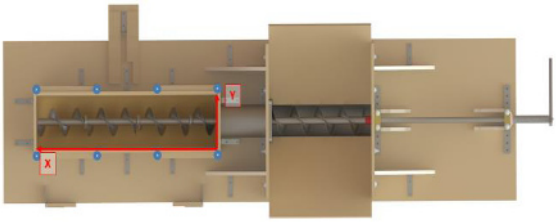
The setup is composed by a 1:1 scale 140kW woodchip combustion system [9,10], fed by means of a screw conveyor. A picture of the device is showed in Fig. 1.




(a) Picture of the experimental setup




(b) Side view render of the setup




(c) Top view of the setup

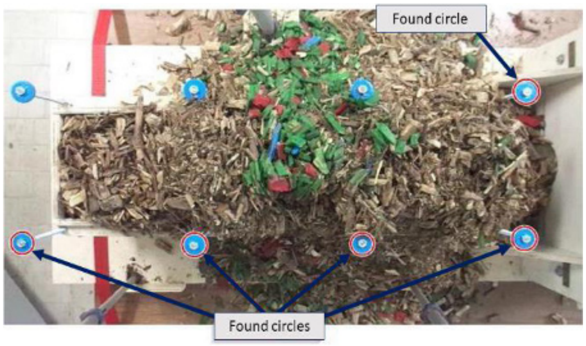
**Figure 1:** Sketch of the experimental setup

The fuel bed consists in a 200 mm height, 150 mm width and 600 mm length box. The screw is a 80 mm pitch and 80 mm diameter device, which can be interted in the fuel bed for a variable length (e.g. see full bed length penetration in Fig.1). In the present work, a screw penetration of 80 mm has been employed. The loading system is also visible in Fig.1, which allows to introduce wodchips into the system by means of the screw rotation. The screw is moved by means of a hand-rotating shaft. Through the described device, the woodchips can enter the fuel bed according to the operation of the combustion system. It is worth to notoce that the fuel leaves the fuel bed when it reaches the top of the bed walls. A Sony DSC-W830 compact camera is placed at 850 mm from the base plate at the center of the fuel bed; its housing is visible in Fig.1a. The camera is oriented to acquire the frames parallel to the bed surface.

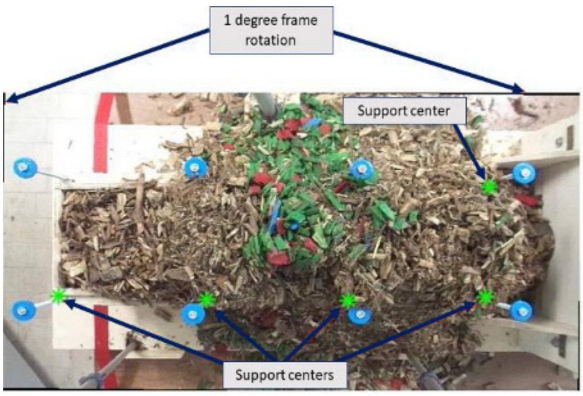
During the test, colored particles are mixed to the woodchips. On total, 6 kg of woodchips (i.e. standard particles) and 1 kg of tracers (i.e. the colored particles) are used during each test. The tracers are made by the same woodchips particles which were previuolsy treated. Firstly they were divided in three main dimensional ranges i.e. 8-16 mm, 16-45 mm, and 45-63 mm according to EN ISO 18847:2016. Secondly, three spray paints i.e. green (RAL 6001), red (RAL 3001) and blue (RAL 5015), respectively for each diensional group, were used to color the woodchips. During this process, negligible variation of woodchips density were achieved, thus resulting below 5% difference in comparison to the standard particles. After standard particles are inserted in the loading system, the screw is rotated until the steady state operation of the system is reached. Hereafter, tracers are loaded in the device and the video recording of the fuel bed surface started.

### 2.1 Pre-processing: view area calibration

An optimization of the view area is made to reduce the analyzed frame exactly to the fuel bed area, reducing the computational cost of the analysis.




(a) Circle detection




(b) Frame rotation and support base point calculation

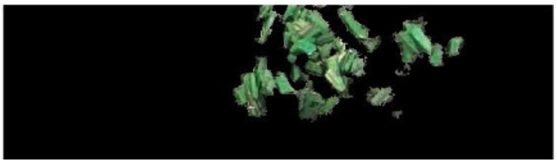
(c) Cutted frame to the post-processing

**Figure 2:** Frame calibration process

However, vibrations or little misplacements can lead to produce frames with uncontrolled length distortion. In order to calibrate the frames while the process is ongoing, eight orientation circles are placed on the top of the bed (Fig. 2a). For each video-frame, these circles are detected, and the image is aligned and centered. Firstly, the circles are detected by using a HSV color filtering approach and a circle finder algorithm avilable through a Matlab routine (i.e. the *imfindcircles* routine). This routine can detect circular shapes whose radii are approximately equal to the desired radius through a circular Hough transform [11,12]. The position of the circles is used to rotate the frame in order to achieve an horizontal orientation of the picture. In this configuration, the position of the circles supports is univocally determined by the circles center position through an experimental calibration process, given the fixed camera height. The calibration process allows to assign to the pixel length of the frame a proper values in millimiters. During this process, not all the circles are automatically detetcted; however, only a partial amount of them are necessary to properly configure the image for the post-process. Finally, the image is properly cutted and referenced to the axis as shown in Figs. 2b and 2c for the further analysis.

### 2.2 Image processing

The cutted frame from the pre-processing is converted from RGB structure to a HSV structure. The HSV (i.e Hue, Saturation, Value matrix) allows the definition of the colors by means of a color wheel (i.e. the colors are on a 360° angle span), which enhance the red, blue and green detection with respect to RGB standard structure [13]. Artificial lights are used during the experiments, and the Saturation and Value ranges are experiemntally tuned and fixed.



(a) 8-16 mm fraction

(b) 16-45 mm fraction

(c) 45-63 mm fraction

**Figure 3:** Tracers detection process

At this stage, different tracker dimensional class can be detected on the bed surface as shown on Fig.3, based on the cutted frame in Fig. 2c.In a further step, the whole frame is divided in several sections to calculate the single color share in each image. The mesh size is chosen to contain at least the biggest tracked particle. In particularly, 18 columns and 3 rows mesh is used to analyze the tracer share. Mesh size dimension is assumed to be known due to the calibration procedure operated with a frame pre-processing. Fig.4 shows the 54-cell grid used to calculate the colored share of particles. The share of the single color (i.e. a single tracer particle dimensional type) on the bed surface is defined as the ratio of the colored particles per mesh and the total mesh surface. This value is further associated to the mesh centroid position and interpolated to produce contour maps.

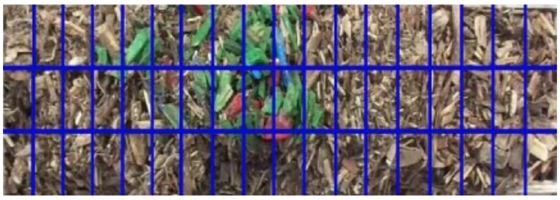


**Figure 4:** Mesh grid used for colored particle share calculation

(a) Example of a raw image

(b) Green particle area, black and white border highlight

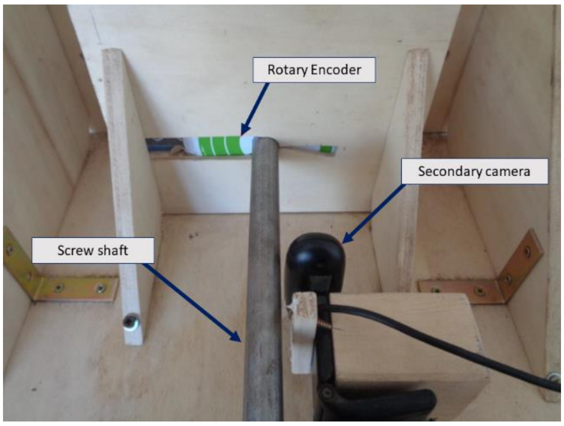
(c) Green particle area detection

**Figure 5:** Macro particles identification process

After the coloured share, single particles macro-groups are detected and tracked during the test. By considering the HSV structure, three images per frame are extrapolated according to the different particle colors (similarly to Fig. 3). Each one is then transformed in a black and white image to highlight the contrast with the colored region border, and noise is reduced by means of hole filling algorithms available on Matlab® (i.e. through the *imfill* routine [14]). Through this process, some particles may appear as overlapped, or too close to be recognized as a single woodchip. In these cases, the tracked position are assigned to a macroparticle group. An example of green elements detection strategy is shown in Fig. 5. It is worth to notice that the particle detection works with minor failure even when high brightness variation are present (Fig 5a). This is mainly due to the HSV structure, which separates the color values from their brightness, thus resulting in less sensitivity to the lighting of the system. Finally, the Matlab *regionprop* algorithm was used to measure the properties of specific image regions such as the colored particles centroid position. Therefore, the centroid position of each group of macroparticles is calculated, and is further related to the screw turn number according to a sinchronization process between the video frames and the screw position.

### 2.3 Screw conveyor turns acquisition

The screw conveyor was hand rotated to allow the woodchips entering the bed. The screw turn number is acquired by means of a second video recording system (Fig. 6a). A rotary encoder (Fig. 6b) was fixed to the shaft and a second camera was used to acquire the color change in a small window, thus indicating the turn advancement.




(a) Turn number acquisition system

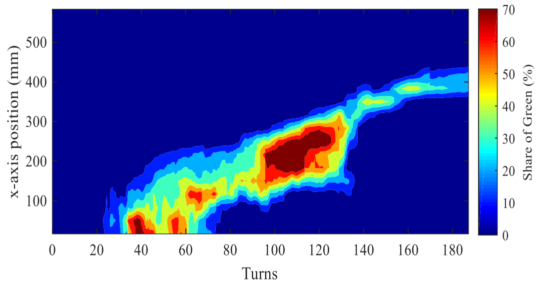
(b) Employed encorder

**Figure 6:** Secondary camera for time-synchronization process

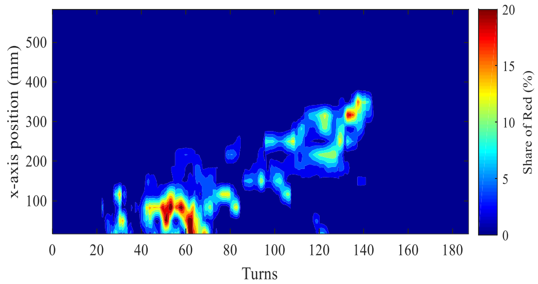
By simultaneously starting both the video recorder systems (one for the particle tracking, and one for the screw turn number) it was possible to easily synchronize the frame acquired from the top of the fuel bed surface and the ones for number of screw turns. In order to check the turns acquisition system consistency, a rotative resistance, an Arduino Nano based system and an LCD display for visual feedback was also employed, thus qualitatively monitoring the screw rotation velocity and the turn number of the shaft. The resistance was powered by a 5V supply, and the signal varies from a maximum to a zero potential over a rotation of 360°. By measuring the pulses and acquiring the potential as a function of the time, it was possible to evaluate the screw turn number and also the shaft angular speed. During the tests, the speed was always kept within the 4 rpm to 11 rpm interval, thus inducing relatively low velocities of the particles. According to this, the system can be considered as quasi-static and the particle tracking was performed as a function of the screw rounds.

## 3 Results and discussion

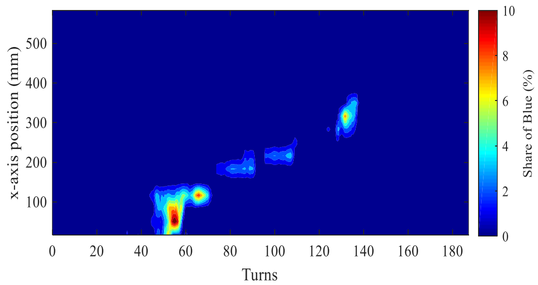
The particle relative share over the time is reported through an interpolated map as a function of the x-axis length in Fig. 7.




(a) Green share




(b) Red share




(c) Blue share

**Figure 7:** Relative share of tracker

The employed method allows to monitor the evolution of the particle share as a function of the screw turns. From Fig. 7, an advancing front is noticeable along the x-axis for all the considered dimensional range. The x-axis position grows almost linearly with the shaft turns. The tracer share significantly drops above 140 turns and around 400 mm x-axis length, which may indicate the woodchips preferential exit area, thus defining a residence time for the particles of around 120 turns with the present configuration. The total surface share of particles divided per dimensional class is showed in Fig. 8 (i.e. the share of a single dimensional group with respect to the total surface).

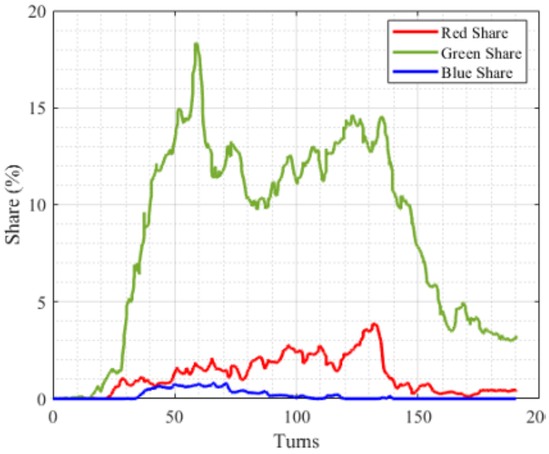
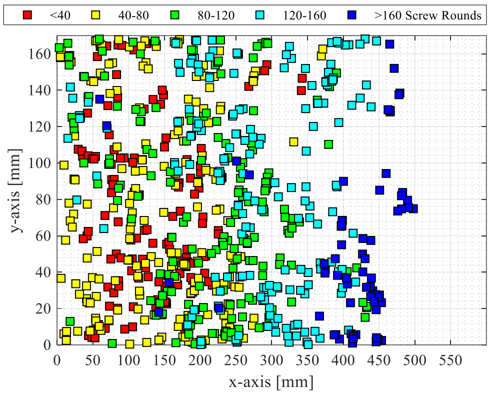
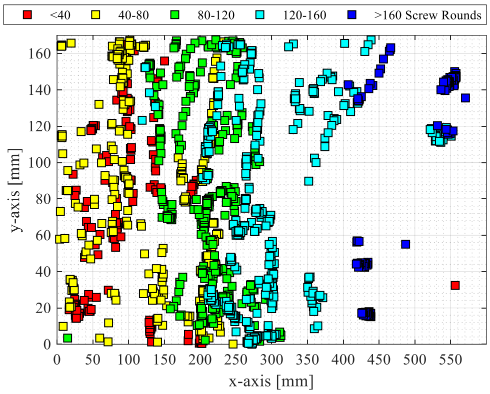



**Figure 8:** Total share of tracers

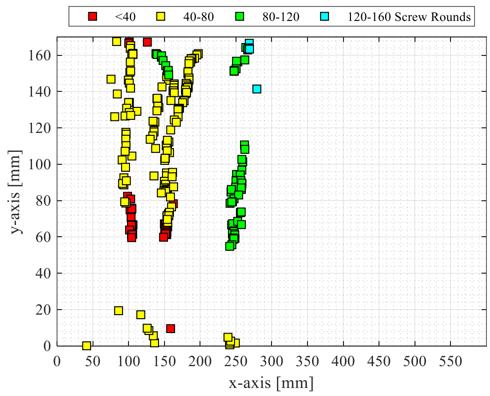
Fig. 8 shows two main peaks on the total share which can indicate the presence of two separate tracer streams generated by the screw movement. Therefore, these woodchips may reach the surface of the bed at two different residence time. Blue particles have significantly lower surface share. This can be related to their high volume and hence high friction, which reduces their movement capability. Since the green and red particles move locally faster, blue woodchips may be quickly covered by fresh fuel in the supply process, thus disappearing from the surface .Fig. 9 shows the position of the centers of the macroparticles along the time. For practical reasons, only a part of the tracked particles is visualized. The presence of an x-axis advancing front that bends toward y-axis along the time is observed. This can be seen in Fig. 9b, where over 120 rounds the compact woodchips front moving towards the x-axis shift to the right of the bed (i.e. higher y-axis values), thus showing a slope variation in the front advancing lines. Moreover, while green particles positions on the surface is more distributed as a function of the round number, red and blue particles are significantly more gathered at separate time interval, as particularly evident in Fig. 9c. This also shows that red and blue particles pop up in groups at different time interval and different positions, possibly due to a secondary woodchips stream as previously noticed on Fig. 8. Fig. 9b and 9c shows that the main part of the tracers (red and blue) stays on the bed surface within 160 turns, and is manly found below 300 mm on the x-axis position. This fact indicates a possible accumulation area in the first half of the bed, which also shows that the second half of the fixed bed does not participate in fuel replacement, possibly impacting the device performances and combustion behavior.




(a) Green macroparticles (20% of the tracked particles are shown)




(b) Red macroparticles




(c) Blue macroparticles

**Figure 9:** Centers position of the macroparticles along the time

## 4 Conclusion

In the present work, an image analysis method is used to track the macroparticles position on a biomass woodchips fixed bed with a screw conveyor as supply system. The tests were performed on the cold operating system, with no combustion occurring. Part of the woodchips were colored according to their dimensional range and used as tracker. A proper algorithm was developed to identify the tracker size by its color, define and detect the macroparticles center, and track its position as a function of the time from video records of the experiments. Using this technique, the main behavior of the woodchips on the fixed bed was assessed, and it has been shown that it can be a valuable tool to optimize the fixed bed, and to provide data for Discrete Element Models validation.

## 5 References

1. Badshah, N., Al-attab, K. A., and Zainal, Z. A., 2020, "Design Optimization and Experimental Analysis of Externally Fired Gas Turbine System Fuelled by Biomass," Energy, 198, p. 117340.
2. El-Sattar, H. A., Kamel, S., Vera, D., and Jurado, F., 2020, "Tri-Generation Biomass System Based on Externally Fired Gas Turbine, Organic Rankine Cycle and Absorption Chiller," J. Clean. Prod., 260, p. 121068.
3. Al-attab, K. A., and Zainal, Z. A., 2015, "Externally Fired Gas Turbine Technology: A Review," Appl. Energy, 138, pp. 474–487.
4. Amirante, R., Bruno, S., Distaso, E., La Scala, M., and Tamburrano, P., 2019, "A Biomass Small-Scale Externally Fired Combined Cycle Plant for Heat and Power Generation in Rural Communities," Renew. Energy Focus, 28, pp. 36–46.
5. Mahmoudi, A. H., Markovic, M., Peters, B., and Brem, G., 2015, "An Experimental and Numerical Study of Wood Combustion in a Fixed Bed Using Euler–Lagrange Approach (XDEM)," Fuel, 150, pp. 573–582.
6. Wiese, J., Wissing, F., Höhner, D., Wirtz, S., Scherer, V., Ley, U., and Behr, H. M., 2016, "DEM/CFD Modeling of the Fuel Conversion in a Pellet Stove," Fuel Process. Technol., 152, pp. 223–239.
7. Xi, Y., Chen, Q., and You, C., 2015, "Flow Characteristics of Biomass Particles in a Horizontal Stirred Bed Reactor: Part I. Experimental Measurements of Residence Time Distribution," Powder Technol., 269, pp. 577–584.
8. Lachin, K., Youssef, Z., Almeida, G., Perré, P., and Flick, D., 2020, "Residence Time Distribution Analysis in the Transport and Compressing Screws of a Biomass Pretreatment Process," Chem. Eng. Res. Des., 154, pp. 162–170.
9. Caposciutti, G., and Antonelli, M., 2018, "Experimental Investigation on Air Displacement and Air Excess Effect on CO, CO2 and NOx emissions of a Small Size Fixed Bed Biomass Boiler," Renew. Energy, 116, pp. 795–804.
10. Caposciutti, G., Barontini, F., Galletti, C., Antonelli, M., Tognotti, L., and Desideri, U., 2019, "Woodchip Size Effect on Combustion Temperatures and Volatiles in a Small-Scale Fixed Bed Biomass Boiler," Renew. Energy.
11. Atherton, T. J., and Kerbyson, D. J., 1999, "Size Invariant Circle Detection," Image Vis. Comput., 17(11), pp. 795–803.
12. Yuen, H. K., Princen, J., Illingworth, J., and Kittler, J., 1990, "Comparative Study of Hough Transform Methods for Circle Finding," Image Vis. Comput., 8(1), pp. 71–77.
13. Burger, W., and Burge, M. J., 2016, Digital Image Processing, Springer London.
14. Soille, P., 1999, Morphological Image Analysis: Principles and Applications.