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Research Note

Energy and pressure requirement for compression of *Miscanthus giganteus* to an extreme density

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To achieve optimal use of transportation infrastructure in general, the bulk density of the material being transported must be such that the containment structure reaches its weight and volume limits simultaneously. As an example, “gondola type” coal railcar dimensions are designed to precisely accommodate the density of coal in a pile, which is 850 kg m^{-3}. Compressing biomass to the bulk density of coal would have the advantage of potential utilisation of the existing coal logistics infrastructure, as well as allowing co-combustion by adding biomass directly to the coal stream. However, the required material density could be as high as 1657 kg m^{-3}, owing to post-compression rebound and a limited particulate packing density. This paper describes an experiment in which a sample of biomass (*Miscanthus giganteus*) weighing 230 g was compressed to 1767 kg m^{-3}, at an applied pressure of 519 MPa. The test was conducted using a very large Universal Testing Machine, capable of generating a force of 13 MN. The sample was further compressed to a pressure of 756 MPa, shortly after which an explosion occurred, presumably caused by ignition of volatile gases generated by localised pyrolysis through frictional heat generation in the biomass. At the point of explosion, the height of the sample was 8.9 mm. Upon reducing the load to zero, the sample was retrieved and the height was measured at 10.7 mm, yielding an instantaneous rebound percentage of 20.2%. After three weeks, the measured sample height was 11.8 mm, yielding a long-term rebound of 32.6%.

1. Introduction

Transportation of biomass as part of a large-scale bioenergy provision system accounts for a considerable portion of the cost of logistics. Depending upon the biomass densification level and transportation mode, feedstock transportation costs range from 13% to 28% of the total costs of bioenergy production (Miao, Shastri, Grift, Hansen, & Ting, 2012). Minimisation of the transportation costs can be achieved by minimising the fleet size, which can be realised by increasing the bulk density of the material being transported. However, the compression level is limited by the allowable load capacity of on-highway trucks and railcars. In the US, the Department of Transportation (DOT) regulates the maximum allowable gross weight for commercial vehicles on the Interstate Highway System at 36.287 t. The available load capacity is equal to this

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maximum, minus the weight of the truck/trailer combination, which depends on the layout. Flatbed trailer trucks, which are often used for transportation of bales, have a maximum load capacity of 21.77 t. The maximum allowable load width and length are 2.59 m and 14.63 m respectively, and a typical maximum height of the load for flatbed trucks is 2.57 m, leading to a load volume of 97.43 m^3 (US DOT, 2003). Based on these data, the maximum allowable density of biomass transported by a flatbed truck is 223.5 kg m^{-3}. Traditional balers produce densities ranging from 120 to 180 kg dry matter m^{-3}, but with modern high-compression cutting balers, a bale density of 230 kg dry matter m^{-3} is achievable (Lam et al., 2008; Miao et al., 2012). In other words, the weight and volume limits of flatbed trailer trucks in the US are well matched to the density of bales produced with modern balers.

The situation is different in the case of utilisation of railcars for long distance biomass transportation. For instance, "gondola type" railcars, used for transportation of coal, are designed to accommodate the density of loose coal in a pile, which is approximately 850 kg m^{-3} (FreightCar America, Inc.). If similar equipment were used for biomass, optimisation would require compression of the material to the same bulk density value as that of coal in railcars. However, the required material density during compression would be higher for two reasons: firstly, after compression, the material rebounds, which lowers the material density. As will be shown later, the long term rebound of *Miscanthus* after extreme compression was measured as 32.6%. Secondly, the bulk density of a material is always lower than the material density because of porosity. An empirical model termed the ZY-model (Zou & Yu, 1996) has been developed, which relates the porosity of a bulk material to the aspect ratio (defined as the length divided by the diameter) of the loose randomly packed cylinders it is comprised of. Typical gravity flowable biomass cylindrical pellets have a diameter ranging from 6 to 8 mm and a length ranging from 12 to 15 mm (Mani, Tabilb, & Sokhansanj, 2006) yielding aspect ratios ranging from 1.5 to 2.5. According to the ZY-model, the bulk material's porosity in this range is approximately 0.32. To compensate for porosity, the material density must be $1/(1 - 0.32) = 1.47$ times higher than the desired bulk density after rebound compensation being $850{*}1.326{*}1.47 = 1657$ kg m^{-3}. This value was set as the target compressed material "in-mould" density of the biomass.

The biomass compression experiment was conducted using a Southwark-Emery machine, one of the largest Universal Testing Machines in the United States, with a loading capacity of 13 MN. The force acting on the sample was measured with an integral load cell, traceable to the National Institute of Standards and Technology (NIST). A sample of *Miscanthus*, hammer milled to an average particle size of 12.7 mm, was placed between two anvils, and compressed to 519 MPa. At this point, extrusion of the material was observed between the anvil and the steel ring containing the sample. The sample was further compressed to a pressure of 756 MPa, shortly after which an explosion occurred. Post-test inspection of the sample revealed clear evidence of burning. The conjecture was made that the heat originating from friction during the extrusion of the material caused localised pyrolysis, which produced volatile gases that self-ignited, resulting in an explosion.

The first objective of this research was to determine the energy requirement for compression of *Miscanthus* to achieve a bulk density equal to coal in railcars (850 kg m^{-3}), requiring a material density of 1657 kg m^{-3}. A second objective was to determine the rebound percentage of *Miscanthus* biomass after compression under extreme pressure.

2. Materials and methods

The *Miscanthus* (*Miscanthus* × *giganteus*, Poaceae/Gramineae), material used in the experiment was planted at the Energy Farm of the University of Illinois at Urbana-Champaign (lat, lon: 40.065801, −88.208564) in 2004, and harvested in the early spring of 2009. The sample consisted of approximately 60–70% stem material and 30–40% sheath and leaf material. The material was ground with a hammer mill (Schutte-Buffalo Hammer Mill LLC, Buffalo, NY) through a screen with an aperture diameter of 12.7 mm, and pre-compressed to a density of approximately 350 kg m^{-3} using a medium-sized Universal Testing Machine (Riehle, model PS-200). Before compression, the sample had a mass of 230 g and a moisture content of 11.5%. The compression arrangement consisted of two A2 steel anvils that were air-quenched and tempered to a Rockwell hardness of HRC 54. The anvils compressed the biomass material between them, while the material was contained laterally by a steel ring with an inner diameter of 106.7 mm and an outer diameter of 143.5 mm (Fig. 1). Figure 2 shows the complete compression "stack," which consisted of several compression parts that were held between the machine's 914 mm diameter platens—large top and bottom compression disks, top and bottom compression "buttons," top and bottom anvils, and a single Viscount 44 ring keeping the biomass contained laterally. Before compressing the biomass, a compliance test was conducted to determine the compressibility of the compression stack. A force of 6.5 MN (half the machine's capacity) was applied to the compression stack without

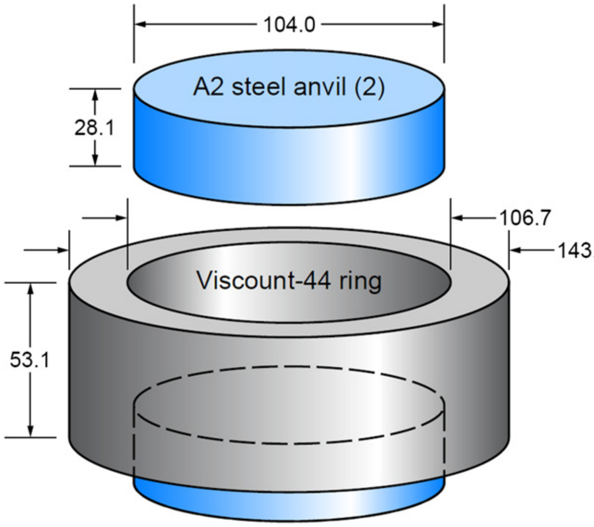

Fig. 1 – Two hardened anvils were manufactured that compressed the biomass sample between them. The sample was constrained laterally using a steel ring. All dimensions are in mm.

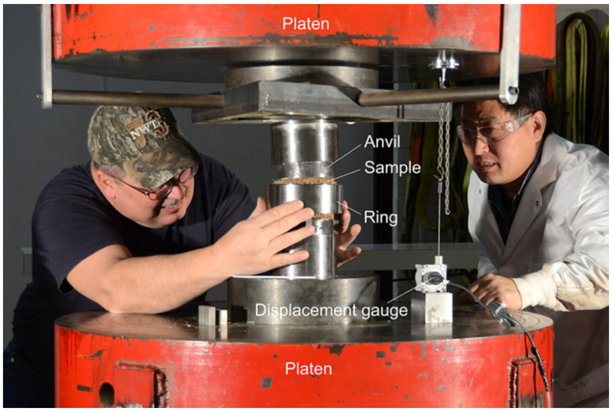

Fig. 2 – The complete compression stack consists of the Southwark-Emery compression machine's integral 914 mm diameter platens—large top and bottom compression disks, top and bottom compression "buttons," top and bottom anvils, and a single Viscount 44 ring that keeps the biomass contained laterally. The force exerted onto the specimen was measured using an integral load cell, traceable to NIST, and the displacement was measured using a displacement gauge. In the photo, technician David Foley (left) and Dr. Zewei Miao (right) are aligning the compression stack.

biomass; this force induced a combined stack displacement of 1.01 mm, resulting in a machine compliance of 0.155 mm MN^{-1}. This value was later used to compensate the biomass compression data for compliance of the compression stack.

Before the test commenced, the biomass was compressed gently until the anvils and the surrounding ring fully contained the biomass (Fig. 2). Subsequently, the sample was compressed while ensuring that the anvils remained parallel to their supporting platens. The entire experiment was captured using a digital video camera.

3. Results

Figure 3 shows the pressure–density curve as observed during compression. The pressure on the sample was calculated from the measured force divided by the inside area of the containing ring. The density of the sample was calculated from its mass divided by the volume of the biomass, which was calculated from the measured height times the inside area of the containing ring. The initial density of the sample was approximately 350 kg m^{-3}, and the first measurable pressure was recorded as the 700 kg m^{-3} density mark was reached. At a density of approximately 1100 kg m^{-3}, the alignment of the containing ring was checked, and repeated at 1350 kg m^{-3}. From that point onward, the sample was compressed to 1767 kg m^{-3} without intervention.

The compression energy requirement was calculated by integrating the measured axial force through the distance travelled during the compression. Figure 4 shows the energy requirement for compression as a function of the instantaneous density of the sample. The units used for energy demand in the bioenergy literature are quite variable; since the objective is to retain the highest amount of energy from crops, it is logical and intuitive to express energy used in the biomass production chain as a percentage of the inherent heating value (PIHV) of the material under test. This heating value of *Miscanthus* was taken as 17.744 MJ kg^{-1} (Collura, Azambre, Finqueneisel, Zimny, & Weber, 2006). From Fig. 4 it can be seen that compression to the target of 1657 kg m^{-3} required only 0.227 PIHV. Even while compressing the biomass to the maximum measured value in the test, being 1767 kg m^{-3}, the energy requirement was only 0.31 PIHV.

At the 1767 kg m^{-3} mark, the material started to extrude through the 1.35 mm clearance between the bottom anvil and the containing ring. Since material was lost from the sample, from this point onward, the measured displacement (and the instantaneous density based on it) was meaningless, but the

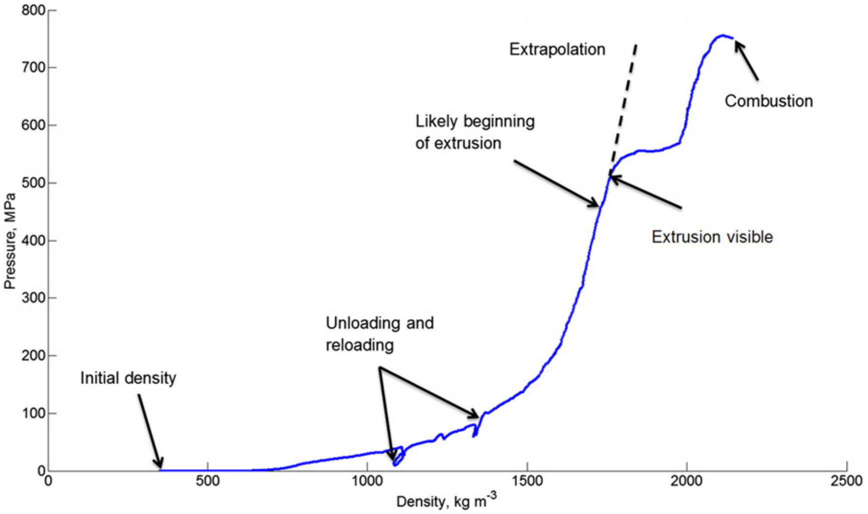

Fig. 3 – The pressure–density curve shows the initial sample density of 350 kg m^{-3}, and an increasing pressure until the sample reached a density of 1767 kg m^{-3}. At this point the material started extruding through the clearance between the bottom anvil and the containing ring. Shortly after the pressure reached 756 MPa, the sample self-combusted. Note that the density beyond 1767 kg m^{-3} is meaningless, since material extruded out of the compression chamber.

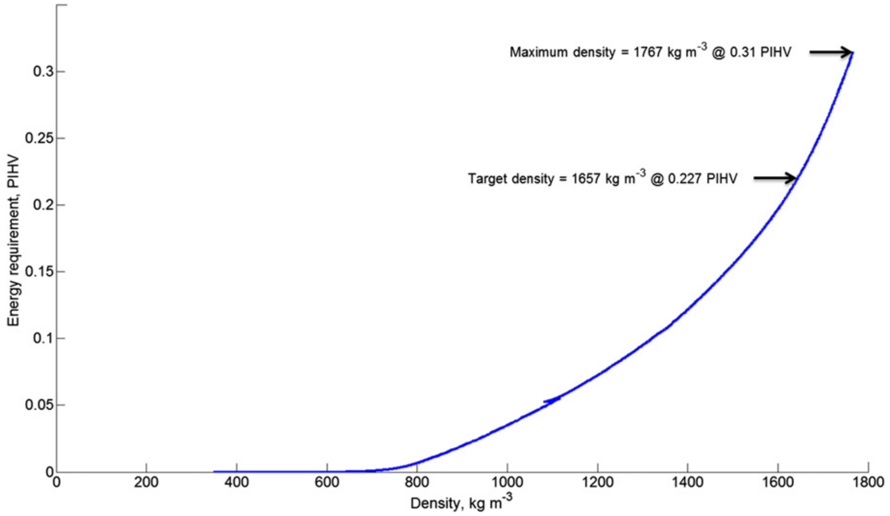

Fig. 4 – The energy requirement for compression of *Miscanthus* was determined by integrating the applied force through the piston displacement. Note that the energy requirement is expressed in an intuitive unit, the percentage of the inherent heating value (PIHV). Overall the compression energy is quite low: Even compression of biomass to an extreme value of 1767 kg m^{-3}, required merely 0.31% of the inherent heating value of the sample.

applied pressure measurement remained accurate since the force exerted onto the sample was measured directly. The material continued to extrude from the sample, until the applied pressure reached 756 MPa, shortly after which an explosion occurred. The force exerted onto the sample at this point was 6.45 MN, approximately half of the machine's capacity. Figure 5 shows three camera frames that depict the biomass being expelled from the bottom of the compression ring. Since the images were taken at 30 frames per second, the material reached a velocity of at least 30 m s^{-1}. In addition, after the explosion, a strong odour of burned material was present. Note that the compression force indicated in Fig. 5 as well as the video has the unit kilo-pounds ("kips"), rather than kN.

Supplementary video related to this article can be found at http://dx.doi.org/10.1016/j.biosystemseng.2012.10.002.

Figure 6 (left) shows the 80 mm tall original sample with a density of 350 kg m^{-3}. On the right, the compressed sample is shown, which clearly exhibits burned areas on its surface.

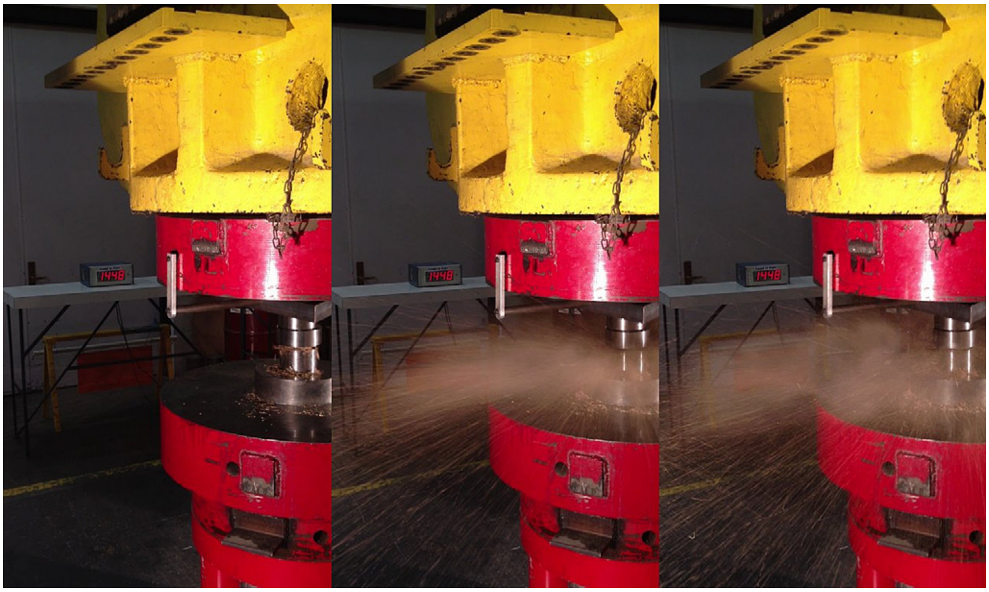

Fig. 5 – The video frames show an explosion that occurred shortly after a pressure of 756 MPa was reached. The explosion was presumably caused by ignition of volatile gases from heat-induced pyrolysis. The material was discharged violently from the bottom anvil clearance. Since the video was taken at a rate of 30 frames per second, the speed of the emanating particulates reached at least 30 m s^{-1}.

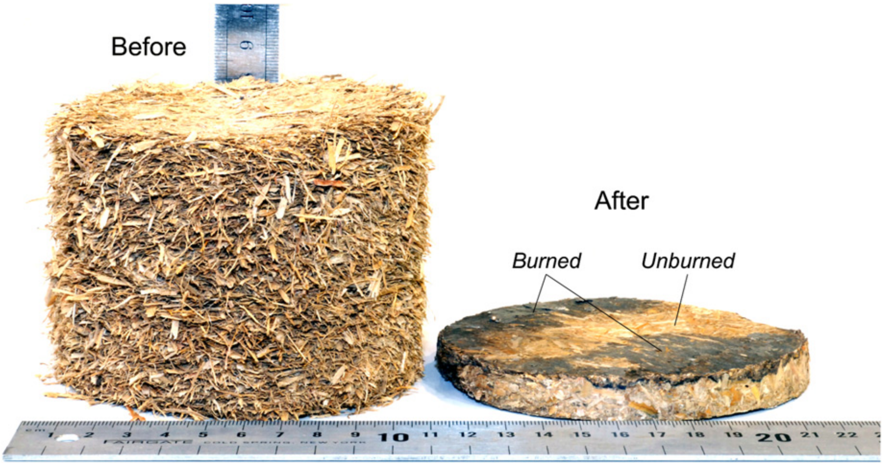

Fig. 6 – Left: Original sample of *Miscanthus* biomass with a density of 350 kg m^{-3}. Right: Compressed sample showing burned areas where self-combustion took place.

Evidently, the friction between the anvil and the flowing biomass created significant heat. The conjecture was made that this heat caused localised pyrolysis, during which volatile gases are produced that ignited causing the explosion observed.

At the point of explosion, the sample had a height of 8.9 mm. After removing the load, the sample was retrieved from the compression chamber, and its height measured at 10.9 mm, yielding an instantaneous rebound percentage of $(10.7 - 8.9)/8.9 = 20.2\%$. After three weeks, the sample height was measured again as 11.8 mm, yielding a long-term rebound of $(11.8 - 8.9)/8.9 = 32.6\%$.

4. Conclusions

To compress biomass particulates such that they constitute a material with a bulk density equal to that of coal in a pile, the material density of the compressed particulates must reach at least 1657 kg m^{-3}. This value was reached by compressing a *Miscanthus giganteus* sample using a Universal Testing Machine with a maximum loading capacity of 13 MN. Care must be taken when interpreting the data as presented in this paper, since it represents a single test, under a single set of initial conditions.

The data showed that to compress biomass to a material density of 850 kg m^{-3}, the required pressure was merely 17 MPa. To obtain the target "in-mould" density of 1657 kg m^{-3}, a pressure of 301.5 MPa was required. The maximum material density achieved during the test (before extrusion of material commenced) was 1767 kg m^{-3}, at a pressure of 519 MPa.

The instantaneous rebound percentage after removal of the load and retrieving the sample was 20.2%. The long-term rebound percentage was determined as 32.6%.

The experiment showed that it is possible for *Miscanthus* material to self-combust when it is allowed to flow in a channel whilst being compressed to over 500 MPa. The presumed mechanism of combustion was localised pyrolysis, in which volatile gases are produced that ignited, leading to the explosion as observed.

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