Conventional and Novel, New Approaches to Creating High-Density Biomass Bales

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ABSTRACT

The costs for harvest, aggregation, storage, and transport of dry biomass are all impacted by bale density. Manufacturers are now offering high-density (HD) balers to meet demands to lower biomass feedstock costs. Field evaluation of HD balers was conducted to quantify achievable bale density and subsequent specific energy consumption (SEC) required to bale common biomass crops. Maximum bale densities were 180 and 240 (kg DM)·m^{-3}, for wheat straw and switchgrass, respectively. Baling SEC increased as a second-order polynomial function of bale density. Although conventional plungerhead balers can create HD bales, the balers are expensive and baling is power intensive, requiring large tractors. We propose an alternative approach where HD bales are created by reshaping and recompressing low-density square or round bales. Pressure-density relationships show that HD recompressed bales can be created with much lower energy requirements than by conventional methods. An alternative, novel approach to creating HD large-square bales by continuous compaction using an auger with compressing rollers was developed and field evaluated. With this technology, square (80 x 80 cm) wheat straw bales in excess of 180 (kg DM)·m^{-3} were produced with the auger baler which is much less complex and lighter weight than a conventional plungerhead baler.

INTRODUCTION

The large-square bale (LSBe) is currently the most common package used to harvest and store biomass feedstocks, primarily because it produces the greatest package density. Bale density has been identified as having the greatest impact on feedstock harvest costs [1]. To achieve legal transport weight limits in many countries, the LSBe density should be about 240 kg·m^{-3} [2]. Using conventional balers, LSBe densities of only 145 to 200 kg·m^{-3} have been reported for switchgrass, wheat straw and maize residue [3-6]. To produce higher-density bales, manufacturers have modified large-square balers (LSBr) to produce greater bale-face pressure by increasing resistance to bale movement through longer bale chambers and greater chamber convergence. Although greater density can be achieved, increased harvest costs due to the more expensive baler, larger tractor required and higher operating costs (fuel, stronger twine, etc.) may overwhelm cost saving in storage and transport [7].

After almost four decades of improvements, the LSBr design is now highly optimized and a marvel of agricultural engineering. But densification by a reciprocating plungerhead may have reached practical limits. Greater bale density is achieved by applying higher pressure to the bale face, but the pressure-density relationship is a power function. After initial void reduction and consolidation, large increases in pressure only produce small incremental density improvements. When applied over the large area of the bale face, even relatively low pressures of 700 kPa will generate tremendous forces and torques which requires heavy frame members, robust driveline components, and large flywheels. Current LSBr use a reciprocating plungerhead with typical frequency of 40 to 50 strokes per minute. Power requirements for densification in this manner are high because of the relatively high-frequency of the tremendous applied loads. What is proposed here are several alternatives that could offer methods to create bale densities even greater than those produced by current LSBr technology, but requiring less power and lighter, simpler machines.

HIGH-DENSITY BALING WITH CONVENTIONAL BALERS

Conventional LSBr have difficulty achieving densities greater than 200 $kg{\cdot}m^{-3}$ for biomass crops [3-6], which is not sufficient for weight-limited transport. We investigated the ability of a HD baler (Krone 1290 HDP XC) to create bales that could achieve weight-limited transport. Assuming bales would be shipped at 85% DM, maximum bale densities achieved were greater than 240 $kg{\cdot}m^{-3}$ for switchgrass, reed canarygrass, maize residue, and sorghum but not for wheat straw (max. of 200 $kg{\cdot}m^{-3}$). Total SEC required from the tractor engine to make bales at the maximum density was 9 to 18 $kJ{\cdot}(kg\ DM)^{-1}$, depending on crop type and yield. Baling SEC increased as a second-order polynomial function of bale density. Precutting increased bale density by 4 to 10% and increased total SEC by 11 to 21%.

RECOMPRESSION AND RESHAPING BALES

Recompressing and resizing square bales is sometimes used to improve transport efficiency, especially for high-quality bales that will be transported long-distances or exported overseas [8]. This process is often done in capital-intensive industrial facilities located off-farm. The added costs of transport prior to recompression may be economical with high-value animal feeds like lucerne but not with low-value biomass feedstocks. What is proposed here is onboard recompression and reshaping of both large-square and large-round biomass bales. In this embodiment, low-density bales would be produced by low-cost conventional baler mechanisms and then the bale would be delivered to an on-board or trailed recompressor. Densification, reshaping and resizing of the first bale would occur in the 30 to 60 s while the next bale is formed. Although densification forces are large, these forces can be applied over a relatively long time so specific energy requirements are much less compared to those required by conventional high-density balers. Current tractors have more than adequate hydraulic flow and pressure to produce the needed forces with reasonable size cylinders. Ingenious designs that place cylinders in tension would reduce required frame size and weight. After densification, there may be sufficient dwell time available for material stress relaxation, allowing the material to lose some of its resiliency before the bale is restrained [9]. Reducing recoil forces reduces bale expansion, maintains achieved density, and allows for lower-cost restraining material to be used. In our research, recompressing LSBe produced re-expanded bale densities of 279 and 282 (kg DM)·m^{-3} for wheat straw and switchgrass, respectively. When compression occurred over less than 25 s, specific energy was less than 1.1 kJ·(kg DM)$^{-1}$. The total force applied by the restraints to prevent bale re-expansion was more than twice that required for HD LSBe.

An alternative recompressed bale system has been proposed that uses a large-round bale (LRBe) for initial harvest and packaging and then uses a reshaping and recompression process to improve bale density, cross-section and transport efficiency [10-11]. We developed a bi-axial recompression system [10] conducted as a three-stage progression: vertical reshaping to cuboid shape, followed by vertical and then horizontal densification (fig. 1). Densities of 240 (kg DM)·m^{-3} was achieved with common biomass crops but density decreased 19 to 30% due to re-expansion after strapping and release of pressure. Recompression over 15 to 20 s required less than 1.0 kJ·(kg DM)$^{-1}$.

An important design aspect of an on-board recompressor is how initial density and the desired final bale size affect the required size of low-density bale before recompression (fig. 2). Low initial density reduces baler costs but increases the size and cost of the recompressor. If a 1.3 m final LSBe length is desired from a single compression charge, then very low initial bale density may be unrealistic due to the required length of the recompressor chamber. Alternatives such as multiple recompression charges or combining two recompressed bales are potential solutions but will add to design complexity. A successful recompressor design will balance the baler cost savings due to low initial density requirements with the size and complexity of the recompressor.

Fig. 1: Concentric rings flattened during vertical reshaping and compression (top). During horizontal compression, material will shear and fold along the bale diagonals where the shear stress is greatest (bottom). After [10].

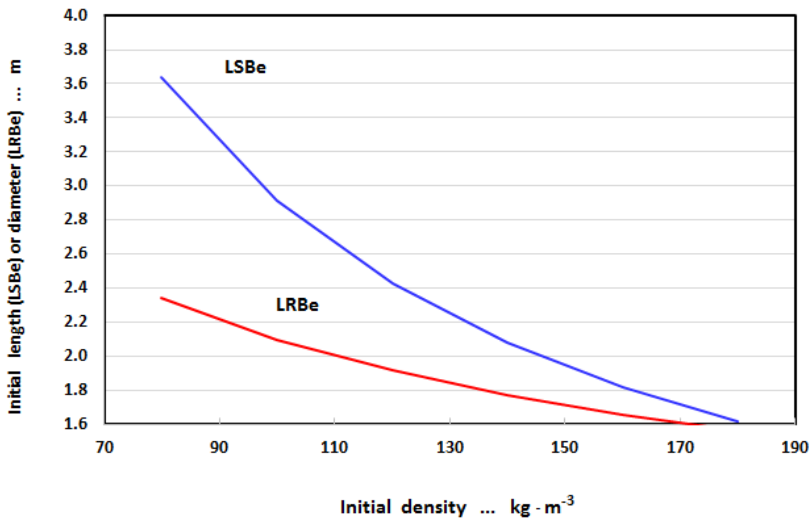

Fig. 2. Initial bale density versus required initial length (for LSBe) or diameter (for LRBe) to achieve 240 kg·m^{-3} final density. LSBe final length is 1.3 m and LRBe final dimensions are a 1.2 m cube.

CONTINUOUS HIGH-DENSITY COMPACTION WITH AN AUGER BALER CONCEPT

Conventional plungerhead balers intermittently compress flakes into a converging bale chamber and compression takes place at relatively high-frequency. We are investigating an alternative baling concept that replaces the discontinuously compressing plungerhead with a continuous feeding auger with a set of conical rollers at the end (fig. 3).

The auger lays thin layers onto the bale face and the rollers flatten the crop as it is laid onto the face. A converging bale chamber with square 80 x 80 cm cross-section is used to complete bale densification. Axial force on the auger is measured and a feedback control system is used to alter tension panel pressure to maintain a target auger compression force. Challenges with this approach include achieving a square bale cross-section from a round auger and segmenting the continuous crop stream into discrete bales. Careful application of auger strippers in the barrel was needed to push crop to all four corners of the chamber [12]. The pivoting bale separation arms are used to cut the bale into discrete lengths and clear a path for the needles to supply twine to the knotters. Bale densities of 230 to 250 (kg DM)$\cdot$m^{-3} have been achieved with crops like switchgrass and maize residue. Baler SEC was typically less than 5 kJ$\cdot$(kg DM)$^{-1}$, comparable to that of a LRBr. The baler mass is 5400 kg, considerably lighter than a LSBr producing similar bale dimensions. The combination of thin-layers and flattened crop help produce high bale densities with a machine that is potentially simpler and more cost effective than a conventional baler.

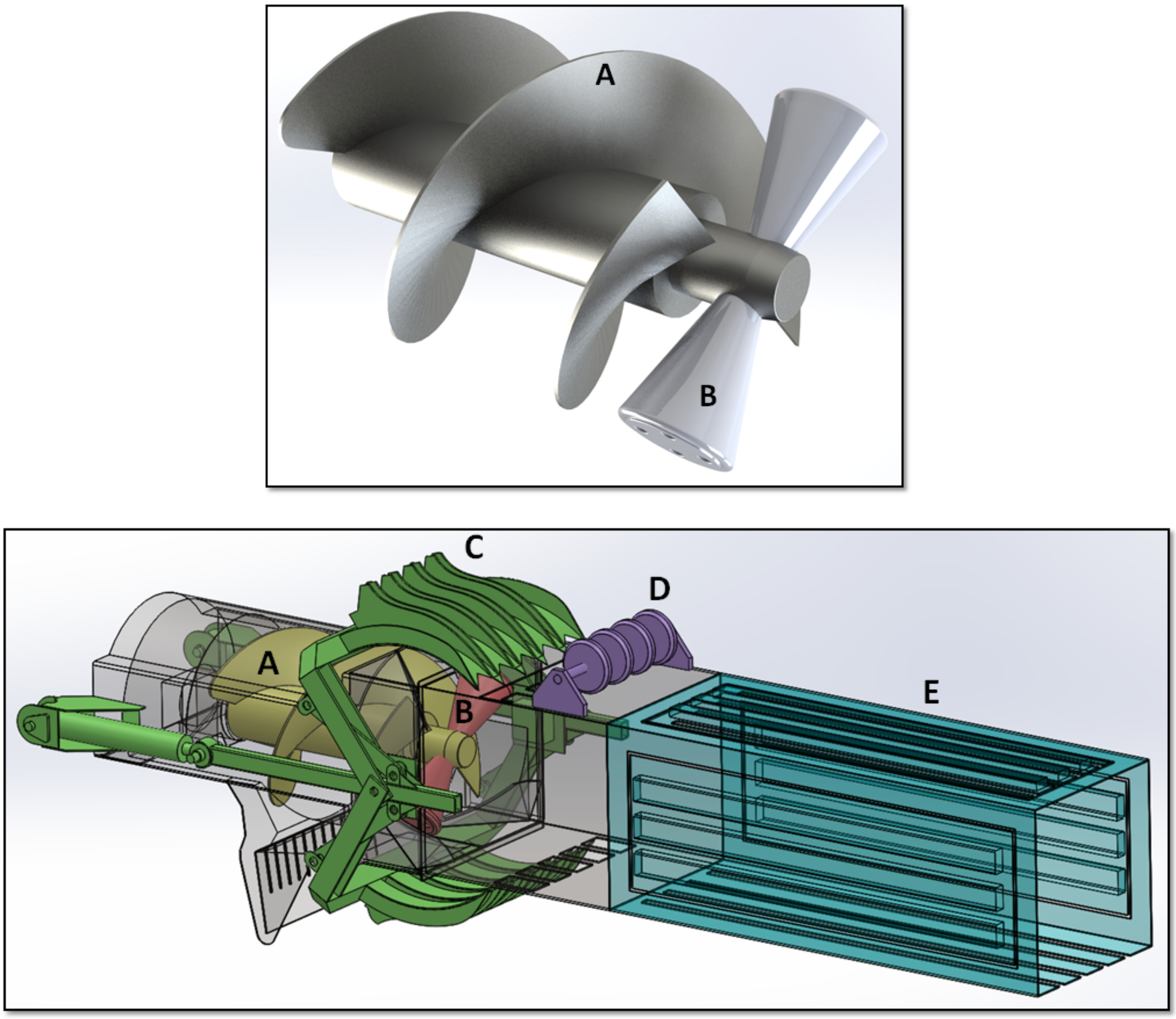

Fig. 3: Auger baler concept consisting of (A) feeding auger; (B) compressing rollers; (C) bale separation system; (D) knotters; (E) converging bale chamber.

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