Temperature During the Vibration-assisted Compression of Alfalfa

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Compression of alfalfa into briquettes is an effective way to solve the problem of storage and transportation. In the process of compression, heat is generated and the temperature is raised in the material. In fact, the appropriate temperature can improve the quality of alfalfa briquettes and reduce the energy consumption of densification. In this study, the effect of assisted vibration on the compression temperature was tested. The results showed that when the vibration frequency was below 15 Hz, the temperature at the center and side in compressed alfalfa increased slowly with compression time. When the vibration frequency was above 20 Hz, it increased first and then decreased with the increase of time. Moreover, the maximum temperature value increased remarkably when the frequency was above 20 Hz. In the same vibration frequency and compression time, the center temperature in the compressed alfalfa was higher than the side temperature. The experimental results provide a reference for the determination of reasonable vibration parameters, and explanation of the effect of vibration on reducing energy consumption.

Keywords: Alfalfa; Vibration; Temperature; Compression

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INTRODUCTION

Alfalfa contains a high amount of crude fiber and important nutrients. It has always been a favorite forage for livestock (Vranic *et al*. 2018; Zhao *et al*. 2019). The loose bulk density of alfalfa is about 20 to 40 kg/m^3. Due to the low bulk density of alfalfa, it takes up a high amount of space during storage and transportation, so the cost of handling and storage of loose alfalfa is high. Densifying alfalfa into briquettes is one of the efficient methods of utilizing it (Fang *et al*. 2018). The process of briquetting involves compressing the loose material into briquettes using a mechanical press. Temperature is an important factor in the process of biomass densification. Proper temperature can reduce the energy consumption of compression and improve the quality of the products (Li *et al*. 2019). Therefore, researching the compression temperature and its distribution in the compressed material will have a significant impact on briquetting.

In densification at room temperature, the compression temperature was mainly generated by the energy caused by the deformation of the material and the friction between the die and the compressed material. Studies have been done regarding the distribution of frictional heat in the die and material during cold pressing, as well as the influence of temperature on the biomass compression process performance (Du *et al*. 2011; De *et al*.

2014; Mikulandrić *et al*. 2016). At room temperature molding, the heavier the friction is, the higher the temperature will be, which will improve the quality of products, but the consumption of compression energy will be greatly increased.

To improve the quality of products, hot pressing has been applied. Hot pressing means that the material is heated to a certain temperature before it is compressed. The studies of hot pressing mainly have focused on the influence of preheating temperature on energy consumption, product quality, physical properties of the briquette during hot pressing, and the determination of hot pressing parameters (Chou *et al*. 2009; Tu *et al*. 2015; Xing *et al*. 2016; Gao *et al*. 2018). Although hot pressing can improve the quality of the densified product, it consumes a lot of energy during the heating process of the material and makes the inner surface of the die become carbonized.

To solve the problem of poor quality of upgraded products and high energy consumption of biomass briquetting at room temperature, some auxiliary compression processes have been considered. Researchers have studied the distribution of temperature in compressed material during ultrasonic vibration-assisted pelleting and predicted the relationship between ultrasonic power and temperature (Song *et al*. 2014; Tang *et al*. 2015; Zhang *et al*. 2016). The making of briquettes and pellets are different with respect to the material state and equipment used, but the compression process and principle are the same. Thus, pellet formation can be a reference for the study of briquetting temperature.

In this study, as an alternative compression process, assisted vibration was introduced into the biomass briquetting, and verification tests were carried out (Wu *et al*. 2014). The temperature for compressing the alfalfa with assisted vibration was studied, to reveal the mechanism of vibration-assisted compression, explain the effect of vibration on reducing energy consumption, and to improve the product quality from the perspective of heat transfer. The results will provide a basis for determination of reasonable vibration parameters in the process of compression.

EXPERIMENTAL

Materials

Alfalfa was used as the experimental material. It was produced at the experimental field of Inner Mongolia Agricultural University (40°48′N, 111°41′E) in Hohhot of China. The material, dried naturally for a long time, was milled into fibrous form by a feed crumbling machine 9RS-60 (manufactured in Machinery Plant of Inner Mongolia Agriculture University, Hohhot, China). The range of particle sizes of the milled raw material was between 2.36 to 3.35 mm, which was prepared according to the GB/T 5917.1 (2008) standard (as shown in Fig. 1). The moisture content was kept around 18% (Cheng *et al*. 2018).

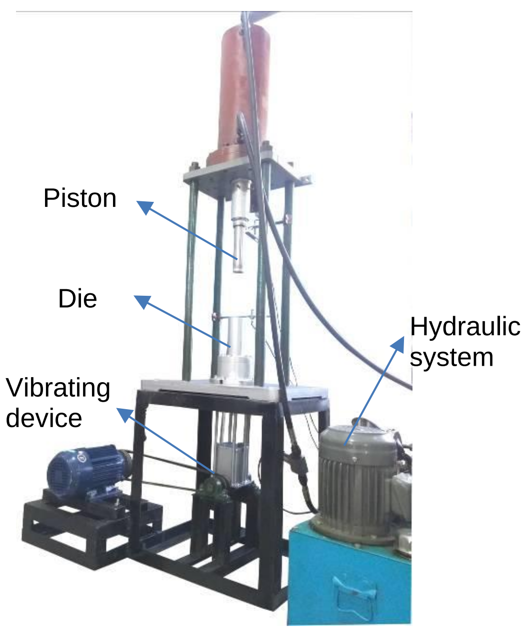
Fig. 1. The experimental material

Experimental Set-up

The experimental set-up designed in this study is shown in Fig. 2a. A cylindrical die with a channel diameter of 45 mm and the length of 120 mm was used to make briquettes from the materials. The compression piston was driven by a hydraulic drive and control system that provided the compression speed of 2.16 mm/s and the maximum pressure limit of 17 MPa.

The assisted vibration with amplitude of 2 mm and frequency range of 0 to 30 Hz was introduced using a crank-slider mechanism, in which the slider pushed the connecting bars and a ring flange that was connected to the ejector rod. Thus, the experimental material in the die was subjected to an axial vibration applied by the ejector rod from below (Fig. 2b).

To compare the effects of assisted vibration on compression of alfalfa, two thermocouple temperature sensors Pt100 (Shanghai Songdao Heating Sensor Co., Ltd., Shanghai, China; Nominal temperature 0 ~ 200 °C, LIN: Under specified conditions, the maximum deviation between the sensor calibration curve and the fitted straight line is the percentage of the full-scale output, ± 0.1%) were employed for measuring the center and side temperature of the compressed material in the die. The signals were amplified by a temperature transmitter (Shanghai Songdao Heating Sensor Co., Ltd., Shanghai, China), and detected simultaneously by a data acquisition board NI USB-6210 (National Instrument Company Ltd., Los Angeles, CA, USA) that was programmed in LabVIEW software (National Instruments Company Ltd., LabVIEW2013, Los Angeles, CA, USA) and logged into a computer.



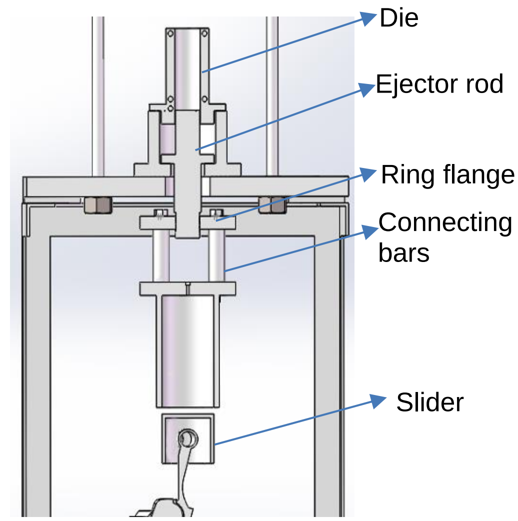


Fig. 2a. The experimental set-up **Fig. 2b.** The vibration device

Methods

The temperature of the die was kept within 30 to 35 °C before compression using a temperature-controlled silicone heating sheet. The prepared alfalfa stalk of 12 g was put into the die, and two temperature sensors were placed in the center of the material and near the side wall of the die, as shown in Fig. 3 (T1 is the center temperature, T2 is the side temperature), then the next alfalfa stalk of 12 g was added to the die to ensure that the sensors were embedded in the material. When the initial temperature of the sensors was kept constant, the compression piston moved down, and the vibration system started to work. Thus, a vibrated compression force was provided to the material in the die. During the tests, the temperature was measured and recorded by a data acquisition system programmed in LabVIEW. To study the influence of vibration on the compression temperature and its transmission in the radial direction of the briquettes, a closed compression die was used in the test. The vibration-assisted compression was maintained for 300 s.

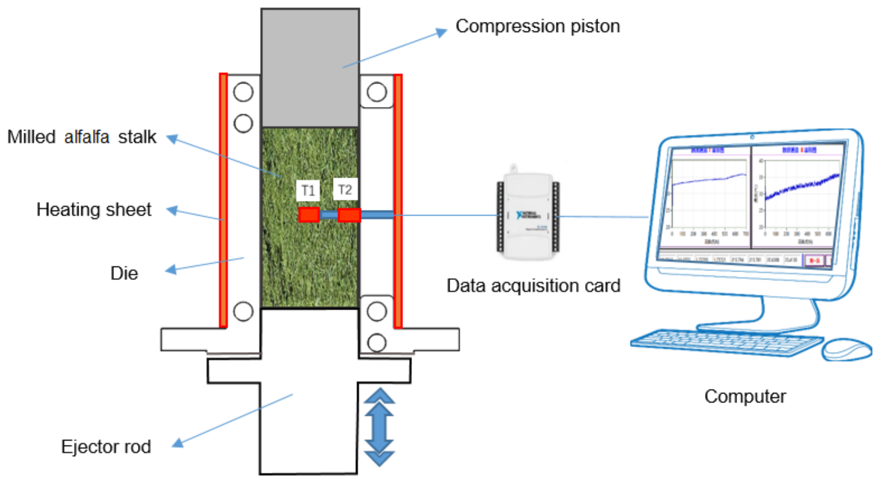


Fig. 3. Arrangement of the temperature sensors

RESULTS AND DISCUSSIONS

The curves of the side temperature and the center temperature in the compressed alfalfa stalk *versus* time based on tested data were made in the software Origin (OriginLab, Pro8, Northampton, MA, USA) at the vibration frequency of 0 and 5 Hz.

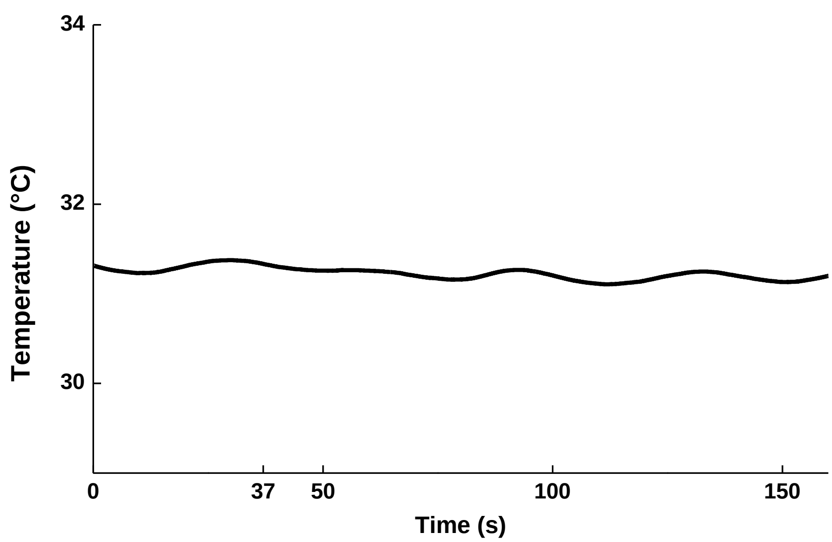


Fig. 4. Curve for the temperature under without assisted vibration compression

Figure 4 shows the curves of the side and the center temperature for 150 s without assisted vibration compression. It can be seen from the figures that there was no obvious change in the temperature at the side and the center during the compression process.

Figure 5 show the curves of the side and the center temperature for assisted vibration compression at 5 Hz frequency. It was noticed that the side temperature and the center temperature exhibited a slow increase trend in the compression process (within 37 s from the beginning); with the increase of holding time (from 38 s to 300 s), both the side temperature and the center temperature slowly increased. In the test stage, the temperature increase value was small, and the center temperature increase value was slightly higher than the side temperature.

This result indicated that vibration could increase the temperature of the compressed alfalfa during the compression process. Under assisted vibration compression, the compression time helped in increasing the temperature of compressed alfalfa in the die.

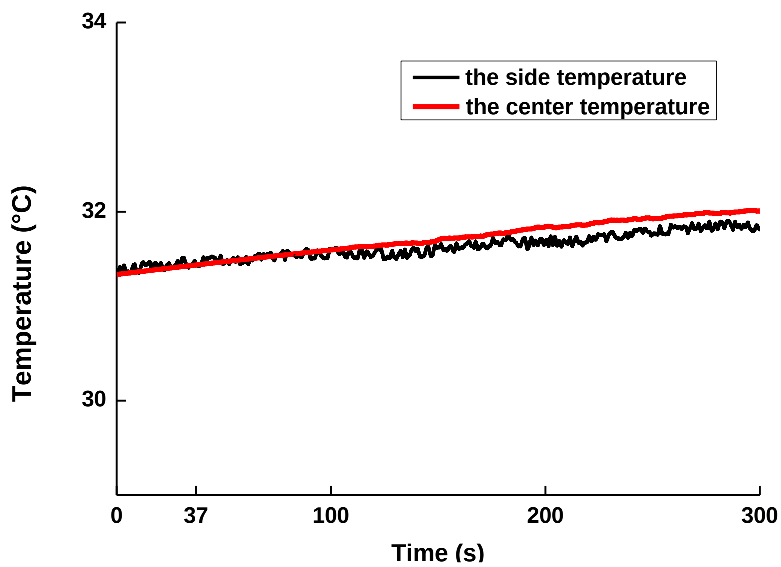


Fig. 5. Curves for the temperature under 5 Hz assisted vibration compression

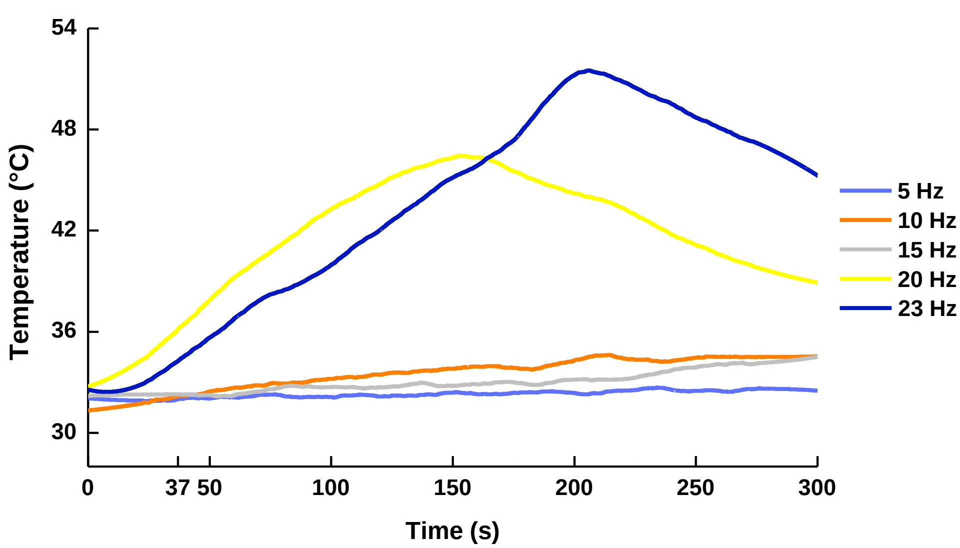


Fig. 6. The center temperature at different frequency vibrations

Figure 6 shows the curves for the center temperature in compressed alfalfa with the compression time under five frequency vibrations. In the frequency range of 5 to 15 Hz, the center temperature in compressed alfalfa increased slowly with the increase of compression time. The maximum increase of the temperature was within 5 °C, showing that the internal temperature rise in compressed material was small under low-frequency vibration.

When the vibration frequency was 20 Hz and 23 Hz, the center temperature in the alfalfa increased at first and then decreased slowly with the increase of compression time. The changing trend was different from that below 15 Hz. The maximum temperature increase was approximately 15 °C at 20 Hz and approximately 20 °C at 23 Hz. From the curves, it was found that the compression time to reach the highest temperature point was different. While the vibration frequency was 20 Hz, the compression time corresponding to the highest temperature point was shorter than that of the 23 Hz vibration frequency. This phenomenon needs to be further tested and verified soon. It can be shown that the center temperature increase in the whole compression process was larger when the vibration frequency was above 20 Hz, and the maximum temperature increase occurred after the alfalfa stalk was compressed for a period of time.

The above results show that the temperature in the compacting material was related to compression time and vibration frequency.

The low frequency vibration (below 15 Hz) had little influence on the compression temperature of the alfalfa stalk. When the frequency was above 20 Hz, the vibration had an obvious heating effect on the compressed alfalfa stalk. This may have been because the vibration caused intense movement of the compressed material and produced a large amount of heat, thus raising the temperature in the compressed alfalfa stalk. The increase of temperature caused the fiber material to soften, especially the lignin in it. The softened lignin acted as a binder so the energy consumption is reduced in the process of material compression (Lee *et al*. 2013; Tumuluru 2014). When the vibration frequency was approximately 20 Hz, the temperature inside the material clearly increased. At the same time, the prior compression force experiments (Xue 2018) showed that the compression force and specific energy consumption were the least when the vibration frequency was approximately 21 Hz, and the quality of alfalfa briquette was better. It was verified that the effect of temperature may be one of the reasons why vibration can reduce the energy consumption.

Based on the test results, the favorable vibration frequency for alfalfa may be around 20 Hz. At that frequency, the heat produced by vibration can make the fiber material soften sufficiently, reduce the energy consumption of compression, and improve the quality of briquettes.

For the vibration compression frequency above 20 Hz, there was a reasonable compression time, which made the temperature increase to the maximum value. The proper compression time could not only make the material fully heated, but also save energy consumption and improve efficiency. It provided a reference for the determination of compression process parameters, such as the length of the die and the time of compression holding time.

Under the different frequency vibrations, the side temperature and the center temperature in the compressed alfalfa in the die had the same changing trend, but the temperature rise was different (Fig. 7).

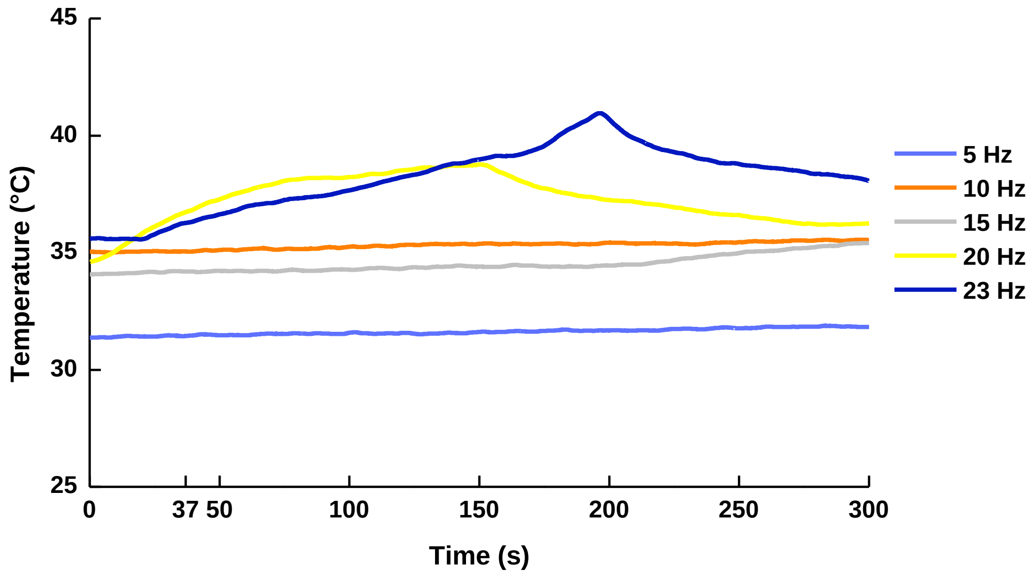


Fig. 7. The side temperature at different frequency vibrations

Figure 8 shows the curves of difference between the center temperature and the side temperature of compressed alfalfa during the whole compression under different vibration frequencies.

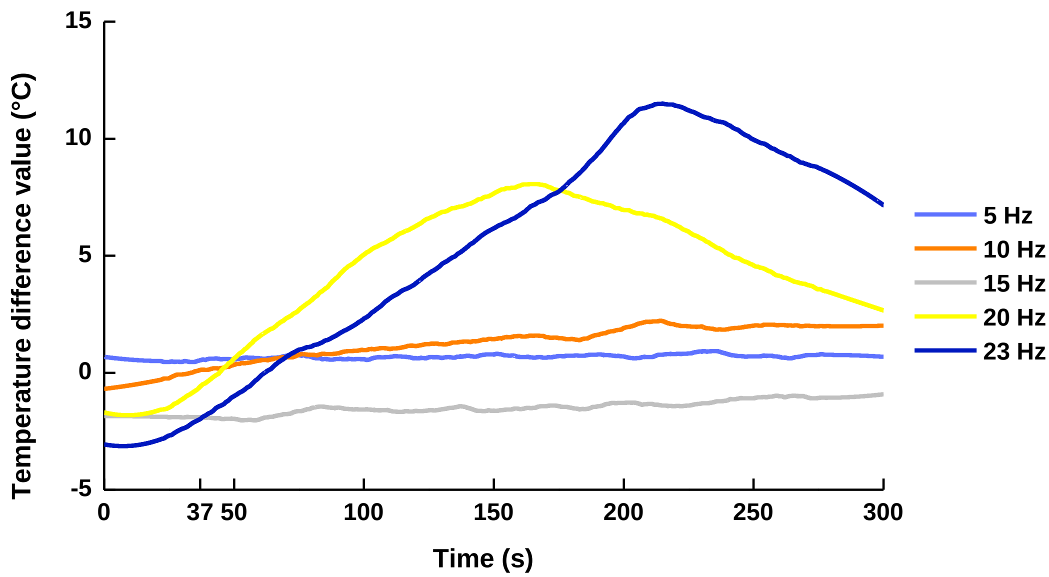


Fig. 8. Temperature difference value at different frequency vibrations

Under different vibration frequencies, the temperature difference at the beginning of compression was negative (except for 5 Hz), which indicated that the center temperature of alfalfa in the die was lower than the side temperature, this was because the die was preheated to approximately 30 °C, which was higher than room temperature. With the increase of vibration-assisted compression time, the center temperature gradually increased and was higher than the side temperature. The temperature difference was more obvious at the frequency 20 Hz.

In the process of compression, the material temperature comes from the energy consumption of compression deformation, the relative movement between materials, and the friction between material and die surface. However, the material temperature in die will transfer to the outside. The temperature in the material depends on the quantity of heat generated and the lost to outside. The main reason for the temperature difference between the center and the side in compressed alfalfa may be the variation of the temperature transmission medium and ways of heat transfer.

The results showed that the temperature generated by the vibration in the material decreased from the center to the outside in the radial direction of the die, which might reduce the carbonization wear of the die and improve die life, but at the same time, might cause the uneven heating of the material and the thermal deformation of briquettes.

CONCLUSIONS

1. Compression temperature was influenced by vibration frequency and compression time. Within a certain compression time, when the vibration frequency was below 15 Hz, the center temperature and the side temperature in compressed alfalfa increased slowly with compression time. When the vibration frequency was above 20 Hz, temperature increased first and then decreased with time. As the vibration frequency rose, the maximum temperature at the center and the side in compressed alfalfa increased. When the frequency was above 20 Hz the maximum temperature value rose remarkably.
2. Under the corresponding frequency, the center temperature in compressed alfalfa was higher than the side temperature. With the increase of vibration frequency, the difference between the center temperature and the side temperature increased.
3. According to the test analysis, the favorable vibration frequency of compressed alfalfa was near 20 Hz, which provided a reference for the future optimal vibration frequency test.

ACKNOWLEDGMENTS

This study was funded by the National Natural Science Foundation of China (Grant No.32060771, No. 31860666) and the project of 2013 Inner Mongolia “Grassland excellence team” (Neizutongzi[2014]27).

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Article submitted: August 11, 2020; Peer review completed: October 18, 2020; Revised version received and accepted: November 1, 2020; Published: November 10, 2020.
DOI: 10.15376/biores.16.1.141-150