Effect of Vibration during Compression on the Process of Making Biomass Briquettes

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An attempt to introduce assistive vibration into the process of biomass briquetting was carried out, with a focus on lowering the energy requirement and improving product quality. The effects of assistive vibration on the surface morphology of briquettes using corn stalk and wheat straw as the experimental materials was investigated, and it was found that assistive vibration can increase the flow capacity of the material and improve the press transmission as well as the uniformity of internal stresses to facilitate the inner-layer-material compression and lower the springback of the compressed material. The biomass particles were still bonded primarily by mechanical interlocking and solid bridges, but the distribution range and size of the voids or gaps between adjacent particles were reduced, and the particles or fibers of thicker layer appeared to be "lying down" instead of "standing," indicating a higher density of the product compared with the case of compaction without vibration assistance.

Keywords: Biomass; Briquette; Assistive vibration; Surface morphology

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INTRODUCTION

Cellulosic biomass, such as agricultural and forestry residues and forage grass, is abundant in China; 700 million tons of crop stalks and 1000 million tons of forestry waste are produced each year (Chen *et al.* 2009; Liu and Zhou 2015). These resources are usually burnt or left to decompose, resulting in environmental pollution and degradation; therefore, the recycling of these materials is urgent and necessary. However, because of their low bulk density and dispersal distribution, they are very difficult to collect, handle, transport, and store in their natural form (Tumuluru *et al.* 2011; Hu *et al.* 2013; Cui *et al.* 2014; Tumuluru 2014). The best solution for this problem is to densify the residual biomass into briquettes, pellets, or logs, which can be readily used as fuel (Kaliyan and Morey 2009; Patrick *et al.* 2014; Bazargan *et al.* 2014). Therefore, briquettes have the potential to be a new energy source to meet the demands of the urban and industrial sectors, thereby making a significant contribution to the economic advancement of developing countries.

Densification of biomass materials is normally done by applying mechanical force to achieve inter-particle bonding. The bonding of particles can be usually understood at the microscopic level using a scanning electron microscope or a transmission electron microscope. The results of previous studies on biological materials compression showed that the bonding mechanism between the particles is mainly solid bridges, and the bonding force between particles is influenced by process variables and biomass properties such as temperature, pressure, binders, moisture, lignin, and protein (Back

1987; Guo 1995; Bika *et al.* 2005; Kaliyan and Morey 2010; Xu *et al* 2010; Huo *et al* 2011).

However, biomass briquetting equipment commonly displays problems of high energy consumption, low efficiency, and rapid wear of key components (*e.g.*, die or screws) because of the springback of viscoelastic biomass and friction between the die and the material during compression, resulting in a higher cost of briquettes used as biomass fuel or animal feed and the restriction of its applications (Mani *et al.* 2006; Jiang *et al.* 2013; Xia *et al.* 2014).

To solve these problems, an attempt to introduce an assisted vibratory force field into the process of biomass densification was performed (Wu *et al.* 2014). This is based on the principle that vibration can reduce the friction between materials and the die surface, assist with compaction, and increase stress relaxation, thus lowering the energy requirement for overcoming springback and improving product quality. The objective of this work was to study the effects of assistive vibration on the surface morphology of biomass briquettes for understanding the mechanism of assisted vibration on biomass compaction.

EXPERIMENTAL

Materials

Two different raw materials were used for the present study: corn stalk and wheat straw, obtained from local Chinese farmers in the Hohhot suburb. The materials were milled into a fibrous form using a 9R-28 crumbling machine (manufactured by the machinery factory of the Inner Mongolia Agricultural University, Hohhot, China). The two types of material had particle sizes between 1 and 4 mm, and they were prepared according to the oscillating screen method using a sieve apparatus (DD CEN/TS 15149 2006). The moisture content of the materials was adjusted to approximately 18% by adding water using a spray bottle and subsequent incubation in a plastic bag for 24 h at room temperature. The moisture content of the milled raw materials was determined according to the technical specifications of DD CEN/TS 14774-2 (2004).

Briquette Preparation

An experimental system was constructed at the machinery factory of the Inner Mongolia Agricultural University, China, as shown in Fig. 1, in which a tapered cylindrical die with an inlet diameter of 45 mm, an outlet diameter of 40 mm, a taper angle of 12°, and a straight, cylindrical section length of 70 mm was used to prepare the biomass briquette logs (100 mm in length) from the raw materials. A punch connected to a piston was driven by a hydraulic system with a maximum pressure limit of 17 MPa; thus, the maximum pressure the punch could exert on the material during the compaction process was approximately 214 MPa. The vibration used to supplement the compaction process was introduced into the punch using an air-operated vibration exciter (Model QJQ3-63; Shanghai YaHong Auto-Controlling Equipment Co., Ltd., Shanghai, China), producing a sinusoidal vibration with an excitation force of 1.7 kN, and a frequency range of 35 Hz (under an air pressure of 0.5 MPa). It is possible to change the vibration frequency *via* changing the air pressure in the air-operated vibration exciter, but the change is limited.

Additionally, the experimental system has the possibilities of adding a supplemental vibration onto the die by another vibration exciter connected to the die *via* connecting bars and a ring flange, and in recording the hydraulic pressure in the cylinder and the displacement of the punch during compression.

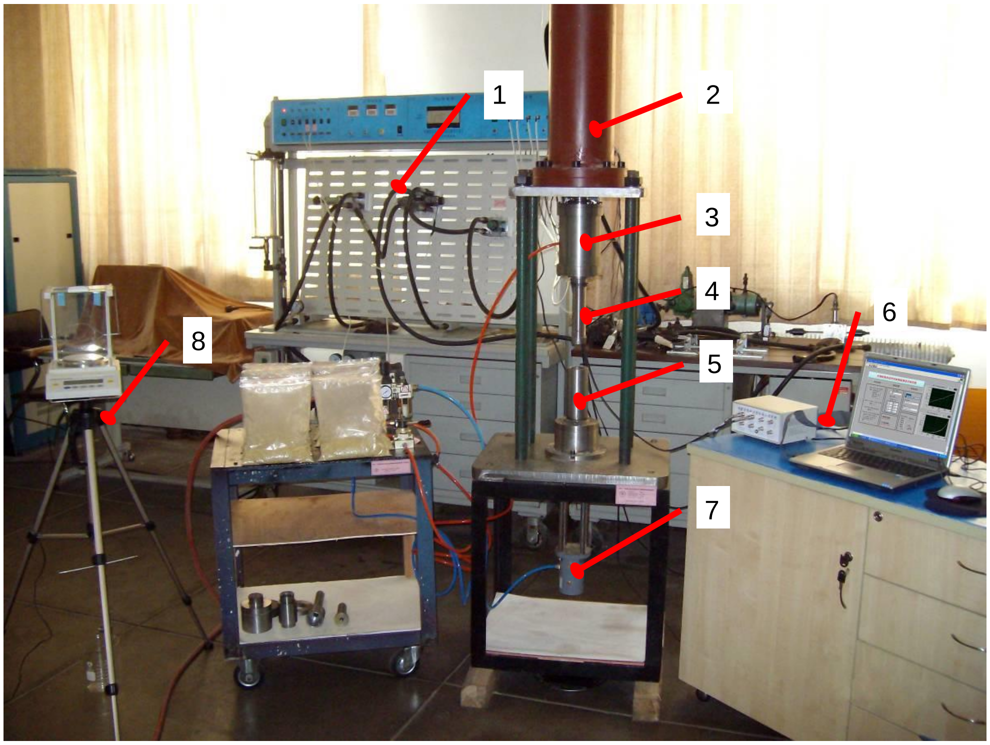


Fig. 1. Photo of the briquette press: 1: hydraulic power system; 2: hydraulic cylinder; 3: pneumatic vibration exciter; 4: punch; 5: die; 6: data acquisition system; 7: pneumatic vibration exciter; 8: density measuring device

Surface Image Preparation

Briquettes made of different materials were prepared under assisted-vibration compression and without assisted vibration to study their surface morphology. Surface images of the briquettes were taken *via* a stereoscopic microscope (ZSA302, Chongqing Photoelectric Instrument Co., Ltd., China) with the following specifications: a total magnification of 7X-50X, an objective magnification of 0.7X- 5X, and a zoom ratio of 1:7, as shown in Fig. 2. A digital camera (Canon PowerShot A650IS, Canon INC., made in China) was used to record the images, and its main specifications are listed in Table 1.

Table 1. Main Specifications of the Digital Camera

Optical zoom	6×	Effective sensor resolution	0.012.1 Megapixels
Digital zoom	4×	Focal length equivalent to 35-mm camera	35–210
Optical sensor type	CCD	LCD screen	2.5
Optical sensor size	1/1.7''	Maximum resolution	4000×3000

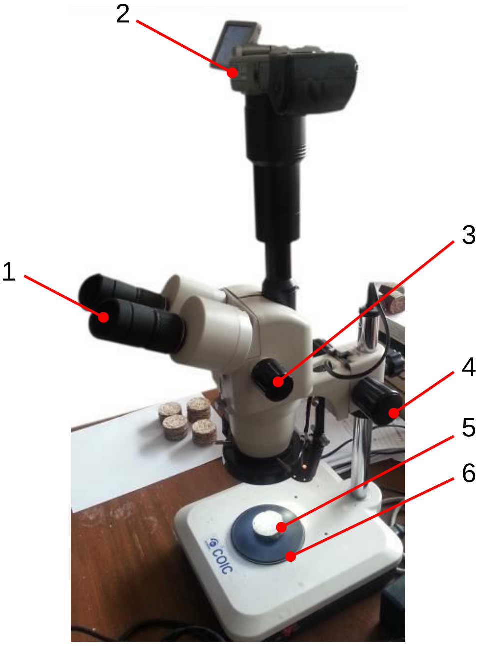


Fig. 2. Picture of the stereoscopic microscope: 1: eyepiece; 2: digital camera; 3: zoom handwheel; 4: focusing handwheel; 5: briquette; 6: stage

The prepared briquettes were fractured into 25-mm-long samples, of which the surface contacted and pressed directly by the punch during the compaction was selected as the observation surface to collect the images. The surface was ground and flattened using a fine sanding machine before observation.

The surface morphology of each sample was observed at two locations on the briquette surface, central, and edge locations (boxes in the images), and for each location, two observing points were selected. To obtain the general profile of the whole surface, the images of the studied surfaces were recorded directly by the digital camera.

RESULTS AND DISCUSSION

Figures 3(a) and 4(a) show the whole-surface images of corn stalk and wheat straw briquettes, respectively, prepared without vibration, while Figs. 3(b) and 4(b) show images of corn stalk and wheat straw briquettes, respectively, prepared with assisted vibration. Two layers from edge to center were observed on the transverse surface of these compressed briquettes prepared either with or without assisted vibration, where the circles in the images approximately show the borderlines between the two layers. In general, the biomass in the outer layer seemed more compact than that in the inner layer, and the particles or fibers at the outer layer appeared to be “standing,” whereas at the inner layer they appeared to be “lying down.”

For both materials, the surfaces of the briquettes obtained with assisted vibration appeared to have a thicker outer layer and a more uniform compact surface compared to the case without assistive vibration, illustrating that the vibration improved biomass compaction, in accordance with the results of the measured relaxation density and relaxation ratio (Table 2).

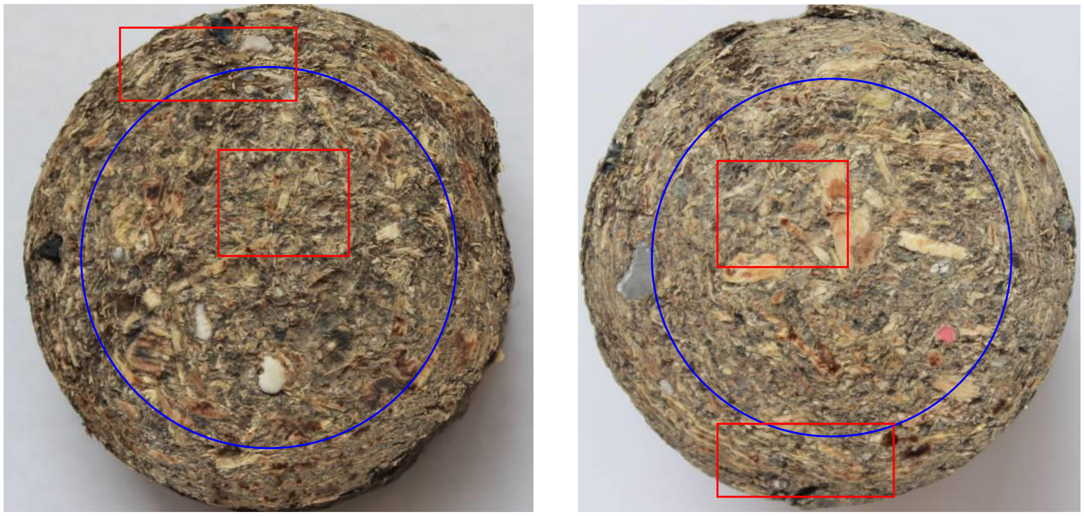

(a) (b)

Fig. 3. Photos of the transverse surface of the corn stalk briquette: (a) without assisted vibration; (b) with assisted vibration

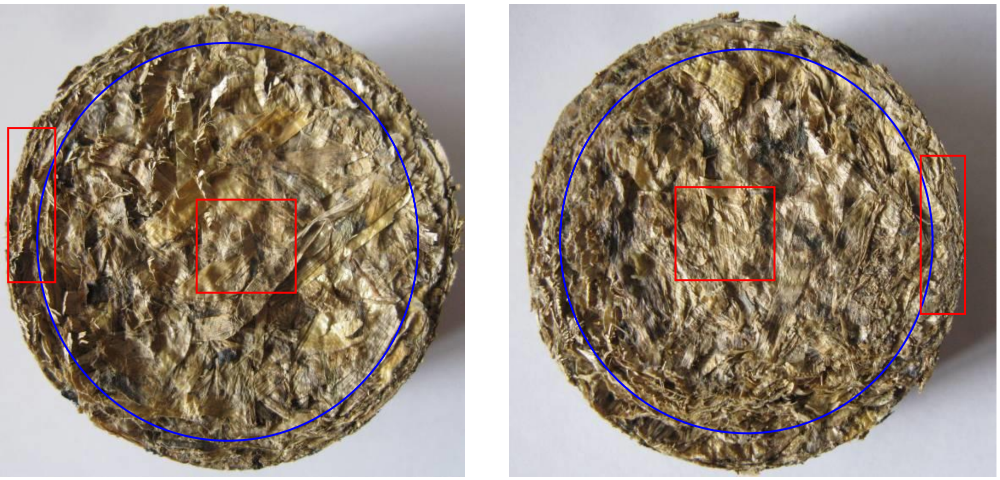

(a) (b)

Fig. 4. Photos of the transverse surface of the wheat straw briquette: (a) without assisted vibration; (b) with assisted vibration

Table 2. Relaxation Density and Relaxation Ratio of the Corn Stalk and Wheat Straw Briquettes

	Corn stalk		Wheat straw	
	No vibration	With assisted vibration	No vibration	With assisted vibration
Relaxation density (g/cm^3)	1.022	1.236	0.71	0.937
Relaxation ratio	1.067	1.041	1.458	1.127

It can be seen from Table 2 that the relaxation density of products obtained with assistive vibration were improved and the relaxation ratios were lowered compared to the case without assistive vibration. These results probably occurred because vibration can reduce the friction between the material and the die surfaces, increase the flow capacity of the material, and relieve or improve the uniformity of the internal stresses, thus lowering the springback of the product. This was in agreement with the results of previous researchers who considered other materials (Jinming 2002; Zhang 2004; Brehl and Dow 2008; Teng *et al.* 2009).

Figure 5 shows the force analysis during the compaction of the biomass in the die (Yin *et al.* 2011). The material fed from the hopper was compressed and moved forward by the punch (force σ_1), which was further compressed (force σ_2) because of the variation of the die section when entering into the tapered section. Then, it was pushed to the straight section of the die after the next charge was fed in. For each feed quantity, a layer of compressed material was formed, and if looked at as a whole, both normal force (σ) and friction force (F) were exerted on the surfaces. Therefore, the material at the outer layer was first compressed, the voids between material particles were eliminated, and material fibers were compressed and crushed; then, these forces on the surfaces were transmitted inward and the material inside was subjected to compaction in succession. Because the biomass is a viscous-elastic material, the compressed material will spring back when the punch is released and the next compression cycle is started. Additionally, there is an energy expenditure when the surface compression force is transmitted inward because of the friction between the particles and the springback of the material, resulting in the material at the outer layer being pressed by a larger force than the inside. This is probably why the biomass in the outer layer had a higher density than the inner layer, and the particles or fibers appeared to be “standing” in the outer layer, but “lying down” in the inner layer.

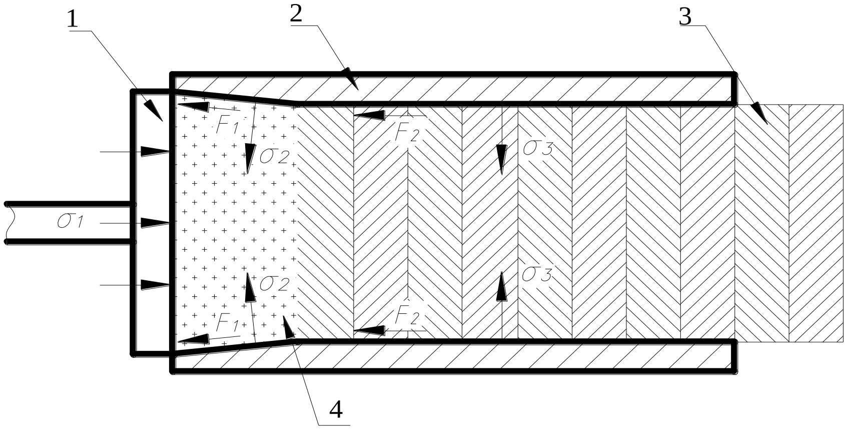
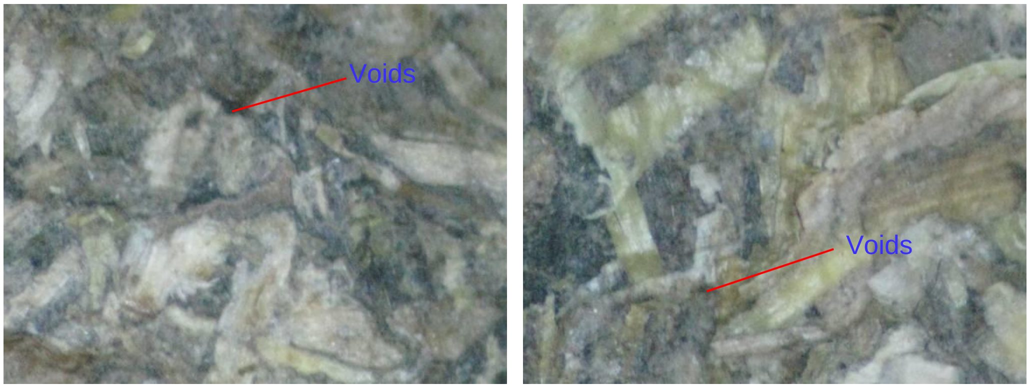


Fig. 5. Sketch of force analysis of the material: 1: punch; 2: die; 3: a piece of briquette; 4: compressed materials

In the case of compression with assisted vibration, the vibration increased the flow capacity of the material, and improved the press transmission and the uniformity of internal stresses. These effects lowered the springback and made the inner-layer material become well-compressed, and finally increased the density of the product.

To further investigate the effects of assisted vibration, magnified images were taken and recorded for both the inner layer and outer layer of each studied surface of the samples. The magnified images were taken by setting the stereoscopic microscope at an eye lens magnification of 10×, an objective lens magnification of 5×, and a digital magnification of 15×.

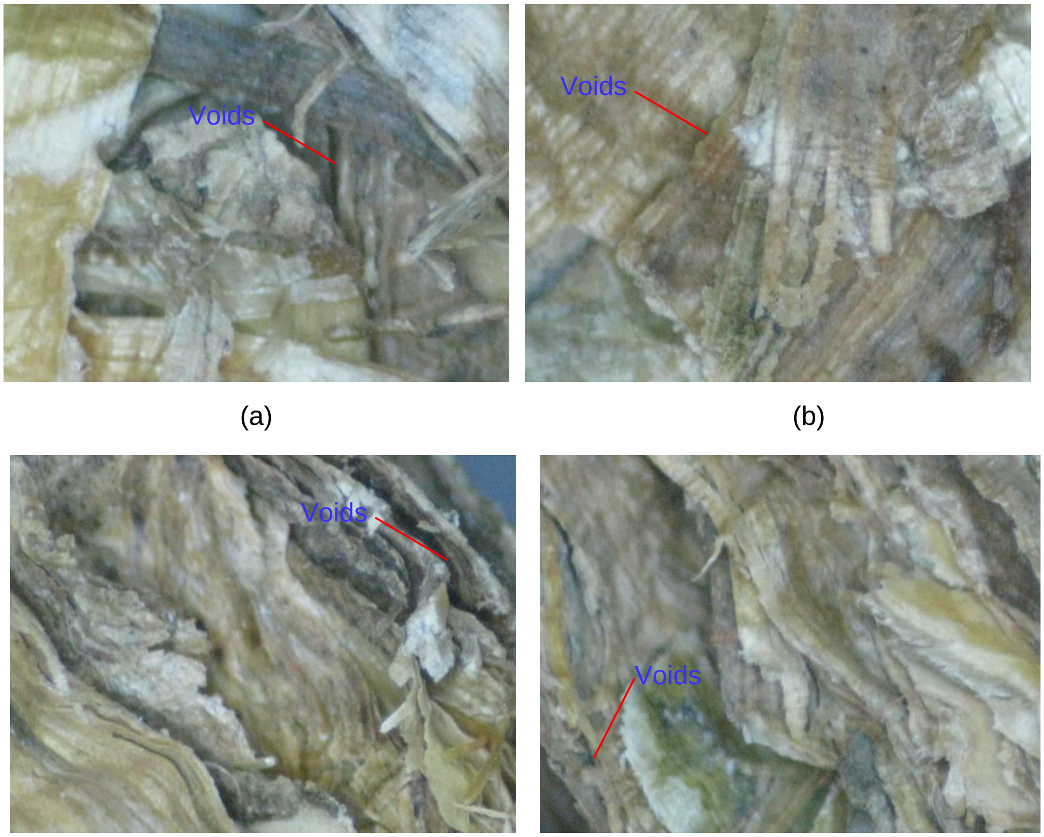


(a) Inner layer (no vibration) (b) Inner layer (with assisted vibration)

(c) Outer layer (no vibration) (d) Outer layer (with assistive vibration)

Fig. 6. Surface morphology of corn straw briquette

Figures 6 and 7, respectively, show the surface morphology of the corn stalk and wheat straw briquettes obtained under various conditions. Similar conclusions can be drawn that the granular materials at the outer layer were in a “standing” state, but at the inner layer they appeared to be “lying down.” And small particles were filled or buried among the big particles; mechanical interlocking and solid bridges between adjacent particles were also observed. With assisted vibration, the bonding mechanism between adjacent particles was not changed, and the particles were still bonded primarily by mechanical interlocking of adjacent particles, but the distribution range and size of the voids or gaps between adjacent particles were reduced (see the marks in Figs. 6 and 7), and the stalk seemed crushed completely. In other words, the particles were bonded tightly, indicating a high density.



(a) (b)

(c) (d)

Fig. 7. Surface morphology of wheat stalk: a) inner layer (no vibration); b) inner layer (with assisted vibration); c) outer layer (no vibration); d) outer layer (with assisted vibration)

CONCLUSIONS

1. The effects of assistive vibration on the inter-particle bonding of the briquettes were investigated by observing the surface morphology of the briquettes, and it was found that the assistive vibration increased the flow capacity of the material and improved the press transmission and uniformity of internal stresses, to thus facilitate the inner-layer-material compression and decrease the springback of the compressed materials.
2. Although the particles were still bonded primarily by mechanical interlocking and solid bridges, the distribution range and size of the voids or gaps between adjacent particles were reduced under the assistive vibration.
3. Two layers from edge to center were observed on the transverse surface of the compressed briquettes prepared either with or without assisted vibration. In general, the biomass in the outer layer seemed more compact than that in the inner layer, and the particles or fibers at the outer layer appeared to be “standing,” whereas at the inner layer they appeared to be “lying down.” For both tested materials, the surfaces of the briquettes obtained with assisted vibration appeared to have a thicker outer layer and a more uniform compact surface compared with the case without assistive vibration, illustrating that the vibration improved biomass compaction.

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