Clustering and modelling of rheological parameters for anaerobic digestion materials (ADMs) and its application for feed pump selection

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Abstract. Anaerobic digestion technology is a promising technology for renewable energy and environmental protection. Rheological properties of anaerobic digestion materials (ADMs) are the essential parameters for transporting and mixing system design. Anaerobic slurry with high total solid(TS) is a Non-Newton fluid fit for power law model, its apparent viscosity is a function of consistency coefficient K and non-dimensional rheology index n. At present, studies on rheological parameters of ADMs mostly focus on specific single raw material, and the TS content has the greatest influence on rheological parameters. By comparing the rheological properties of different ADMs in literatures, it was found that the large difference among the rheological parameters comes from not only different types of ADMs (due to different components), but also the same type (due to different ways of pretreatment), which makes it difficult for the selection of rheological parameter model in biogas design. In this work, 20 different ADMs were clustered into 5 types by statistical method and then their rheological parameters were conducted. The five types of ADMs respectively are: low fiber content slurry, high fiber content slurry, straw manure mixture, straw suspension and digested sludge. The rheological parameter models of the five types can be written as K as an exponential function of TS, and n as a linear function of TS, which the range of TS is 4%-10%. Furthermore, the rheological parameter models were applied to the selection of feed pump of a 6000m\textsuperscript{3} biogas plant in Funan county of Anhui province, China. In this paper, the values of K and n of 20 ADMs were calculated when TS equals to 4%, 6%, 8% and 10%, and the optimal classification results were obtained by comparing the three results between hierarchical clustering method and K-Means clustering method.

1. Introduction
Anaerobic digestion(AD) technology is a promising renewable energy technology and environmental protection technology for biogas production [1]. The implementation of the AD technology is by means of sending the ADMs into continuous stirred tank reactor (CSTR) and stirring the ADMs continuously [2]. Generally, ADMs include livestock and poultry manure [3][4][5], crop straw [6][7], kitchen waste and municipal sludge [8] [9]. The ADMs of high solid(TS) content and high fiber content show the Non-Newtonian fluid of power law rheological behavior [10][11][12]. This rheological property is determined by consistency coefficient K and non-dimensional rheology index n [13]. Rheological parameters are the essential parameters for feeding system and mixing system.
design, and the incorrect selection of rheological parameters can result in the congestion of the pump and even the destruction of the pump.

A large number of literatures studied the rheological properties of ADMs and obtained the values of K and n at different TS-content [5][14][15][16]. Comparing with the data in literatures, it can be seen that the large difference of rheological parameters in different types of ADMs. Tian LB et al [7] carried out the K value is of 1.5-8.4 Pa s^{−1} and the n value is of 0.42-0.25 of corn stalk in 20 mesh at the TS-content of 4.23%-7.32% [17]. Achkari-Begdouri and Goodrich measured the K value of 0.042-5.885 Pa s^{−1} and the n value of 0.42-0.25 with Mexican cow manure at TS-content of 2.5%-12.1% [17]. At the same time, the rheological parameters of the same type ADMs were also quite different. Langner JM obtained the K value of 0.1407-3.9 Pa s^{−1} and the n value of 0.5516-0.6798 with pig manure at TS-content of 5.15%-12.9% [18]. And Shi HX carried out the K value is of 0.001-6.973 Pa s^{−1} and the n value is of 1.03-0.18 [5]. The difference of the rheological parameters among the ADMs comes from the difference of fiber content and the methods of pretreatment [10]. The two reasons above result in the difficulty of selection of ADMs rheological parameters in the biogas plant design.

In this work, clusters of 20 ADMs were carried out using multivariate statistical method. Several clusters with large difference of rheological parameters were obtained. And then models of the clustered ADMs were obtained. At last the models of rheology parameters were applied in the selection of a 6000m³ biogas plant design in An Hui province of China.

2. Materials and method

2.1. Modelling of rheological parameters

2.1.1. Rheology model. Generally, the AD slurry in CSTR has the rheological property that fit for Power law model [5][10][15], see function (1). According to Newton inner friction law, the relation of apparent viscosity as the function of shear rate can be described in equation (2). Combined equation (1) with (2), the apparent viscosity is defined as equation (3). This work only focus on the influence of TS-content on rheological parameters K and n because of the dominate role of the TS-content comparison with the temperature.

\[
\tau = K\dot{\gamma}^n \tag{1}
\]

\[
\tau = \eta\dot{\gamma} \tag{2}
\]

\[
\eta = K\dot{\gamma}^{n-1} \tag{3}
\]

Where, \(\tau\) is the sheer stress[Pa]; \(\dot{\gamma}\) is the sheer rate[s^{−1}]; \(\eta\) is apparent[Pa s]; K is the consistency coefficient[Pa s^{−1}]; n is the non-dimensional rheology index n.

![Figure 1. Schematic of procedure of clustering and modelling of rheological parameters for anaerobic materials.](image_url)
2.1.2. Modelling. The procedure of the establish of the rheological parameters (see Figure 1) is as follow: firstly, the data of ADMs are acquired, and scatterplots of K and n are calculated. Secondly, choosing the appropriate clustering method for the clustering of different rheological parameters, and acquired some clusters with large difference of rheological parameters. At last, models of the clustered ADMs are carried out.

Table 1. Data source of 20 different anaerobic digestion materials.

| Serial number | Symbol of materials | Material name                          | Data sources |
|---------------|---------------------|----------------------------------------|--------------|
| 1             | zf1                 | Manure slurry                          | [11]         |
| 2             | zf2                 | Sieved pig manure in anaerobic pond    | [18]         |
| 3             | zf3                 | Fresh sieved pig manure                | [5]          |
| 4             | zf4                 | Anaerobic sieved pig manure            | [5]          |
| 5             | zf5                 | Anaerobic pig manure in batches        | [4]          |
| 6             | nf1                 | Fresh Moroccan cow manure              | [17]         |
| 7             | nf2                 | Anaerobic sieved cow manure            | EMs          |
| 8             | nf3                 | Cow manure slurry                      | [19]         |
| 9             | nf4                 | Anaerobic cow manure in the farm       | [20]         |
| 10            | nf5                 | Anaerobic cow manure in batches        | [4]          |
| 11            | jf1                 | Anaerobic sieved chicken manure        | EMs          |
| 12            | jf2                 | Anaerobic sieved chicken manure in batches | [4]     |
| 13            | yj1                 | Mechanical disintegration corn stalk in 20 mesh | [7]    |
| 14            | yj2                 | Corn stalk slurry using two paddle propeller | [6]   |
| 15            | dj                  | Rice straw slurry disintegration in 1mm | EMs         |
| 16            | hh1                 | Mixture of manure and stalks           | [10]         |
| 17            | hh2                 | Crushed pretreatment mixture of manure and stalks | [10] |
| 18            | hh3                 | Uncrushed pretreatment mixture of manure and stalks | [10] |
| 19            | cjwn                | Primary sludge                         | [21]         |
| 20            | xhwn                | Digested sludge                        | [21]         |

2.2. Data source and scatterplot of rheological parameters
In this paper, rheological parameters of 20 ADMs were collected. Pig manure, cow manure, chicken manure, rice straw, wheat straw, straw manure mixture and sludge included. Table 1 listed the 20 ADMs and the data source. For the convenience of analysis, the symbols of different ADMs were used. EMs is the symbol of the data from experiments we did.

The scatterplot can’t be conducted due to the data of rheological parameters of 20 ADMs measured at different TS-content. Therefore, the continuous function of rheological parameter model needs to be established first, after that, value of K and n were obtained at the special TS-content. It was found that the exponential function model is the most suitable model after the curves fit of K and n of 20ADMs. The models of K and n as the function of TS are listed in equation (4) and (5). The value of K and n of 20 ADMs were calculated at TS-content of 4%, 6%, 8% and 10%. K was taken as the x-coordinate and n as the y-coordinate to draw the K-n scatter diagram at the four different TS-content, as shown in figure 2. Then five clusters were acquired from the observation of scatterplot and marked with circles in the K-n scatterplots.
\[ K(TS) = Ae^{b+TS} + C \]
\[ n(TS) = ae^{b+TS} + c \]

Where, TS is the mass fraction of dry basis of ADMs, [%]. A, a, B, b, C and c are constants.

Figure 2. Scatterplot at different TS-content, (a)TS=4%, (b)TS=6%, (c)TS=8%, (d)TS=10%.

2.3. Clustering methods

2.3.1. Clustering algorithm. Cluster analysis is a multivariate statistical method for studying classification problems known as unsupervised learning. Clustering algorithm is divided into Hard Clustering and Fuzzy Clustering [22]. There are four types of hard Clustering: Partitioning Clustering Method, Hierarchical Clustering Method, Density-based Clustering Method and Grid-based Clustering Method.

Partitioning Clustering Method is a prototype-based classification method that the samples are divided into the classes by distance corresponding to the cluster center, typically as K-means Clustering which is suitable for data sets with convex shape and similarity of data size and density. Hierarchical Clustering method can achieve the hierarchical decomposition of a given dataset by merging the samples with similarity or distance, which is suitable for clustering problems with similar size and spherical object distribution. Density-based Clustering method [23] is developed to find clusters of arbitrary shape according to the high density area of the sample space, which depends on the selection of the neighborhood radius of core point and the high density threshold. The realization of Grid-Based Clustering Method and Fuzzy clustering method are both need two input parameters.

2.3.2. Clustering method selection and algorithm implementation. Both hard clustering method and fuzzy clustering method are based on the distance between samples. Results are objective of Hierarchical Clustering method and K-means Clustering method with only one parameter needed than the other clustering method with two parameters needed. Meanwhile, the Hierarchical Clustering method has been applied in the classification of biomass materials [24]. So, the Hierarchical Clustering method and K-means Clustering method were used in the clustering of 20 ADMs.

The procedure of Hierarchical Clustering method and K-means Clustering method is as follows: data standardization, calibration and clustering. The standardization of data can eliminate the influence of units of rheological parameters and equation (6) is the standardization equation. The similarity
between samples is calculated by distance and similarity coefficient. For any m dimension column vector $x_i$ and $x_j$, Euclidean distance is adopted, as shown in equation (7). The flow chart of the two clustering methods is shown in figure 3.

$$x'_{ik} = \frac{x_{ik} - \bar{x}_k}{s_k}, i = 1, 2, \ldots, n; k = 1, 2, \ldots, m$$

(6)

$ar{x}_k$ is expected, $s_k$ is standard deviation.

$$d_2(i, j) = \sqrt{\sum_{i=1}^{m} |x_{im} - x_{jm}|^2}$$

(7)

Where, $x_{im}$ and $x_{jm}$ respectively represent the value of the $m$th attribute of sample $x_i$ and sample $x_i$.

$m$ is the number of attributes contained in a sample.

Figure 3. Flow chart of clustering method: (a) Hierarchical Clustering method (b) K-means Clustering method.

2.4. Evaluation of the two clustering methods

Calinski-harabasz (CH) [25] was used to determine the clustering effect, as shown in equation (8). CH defines the internal evaluation index through the ratio of the degree of separation and the degree of tightness. The larger the CH value, the higher the separation between clusters, which describes the better clustering result. $c$ and $c_k$ are calculated in equation (9) and (10).

$$CH = \frac{1}{M-1} \frac{\sum_{k=1}^{M} |C_k| \text{dist}^2(c_k, c)}{1/n - M \sum_{k=1}^{M} \sum_{x \in C_k} \text{dist}^2(c_k, x)}$$

(8)

$$c = \sum_{x \in X} x / n$$

(9)

$$c_k = \sum_{x \in C_k} x / |C_k|$$

(10)
Where, sample set $X = \{x_1, x_2, \ldots, x_i, \ldots, x_n\}$, $n$ is the data number of $X$, clustering result $\pi = \{C_1, C_2, \ldots, C_M\}$, $M$ is the number of classes, $1 \leq k \leq M, |C_k|$ is the number of data objects in $C_k$. $C$ is the center point of the data set, $c_k$ is the center point of the class $C_k$, $\text{dist}(x_i, x_j)$ represents the difference between the $x_i$ and $x_j$, which is Euclidean distance.

3. Results and discussion

3.1. Cluster results

Clustering method is an unsupervised learning process, and the number of clusters is determined by experience. The discriminant conditions are as follows: (1) the number of classification should be greater than 4, because the selected materials contain at least 4 sets of ADMs: livestock and poultry manure, straw suspension, manure straw mixture and digested sludge; (2) the number of categories should be as small as possible for the convenience of application. Combined with the observation results of the scatterplots, 5 clusters are appropriate. Therefore, the threshold values of Hierarchical Clustering method are 1, 1, 0.7 and 1 respectively, as shown in figure 4. The cluster results of K-means Clustering method are shown in 5 different colours, as shown in figure 5.

3.2. Cluster result analysis

Figure 6 implies CH values of HCM clustering results and K-means clustering results under 4 different TS-content. When TS-content is 4% and 6%, the CH value of K-means clustering method is greater than the HCM clustering method’s, and it is equal when TS-content is 8% and 10%. Meanwhile, by comparing with the two clustering methods, the difference between the types and quantity of ADMs obtained by k-means clustering is smaller than by Hierarchical Clustering method. Therefore, the clustering results of K-means clustering method are more appropriate.

According to K-means Clustering results, 20 different ADMs were divided into five clusters: low-cellulose manure, high-cellulose manure, straw manure mixture, straw suspension and digested sludge.

3.3. Rheological parameter models

![Figure 4](image)

*Figure 4. Results of Hierarchical clustering, (a)TS=4%, (b)TS=6%, (c)TS=8%, (d)TS=10%.*
Figure 5. Cluster results in K-means method, (a)TS=4%, (b)TS=6%, (c)TS=8%, (d)TS=10%.

Figure 6. CH value of Hierarchical Clustering method(HCS) and K-means method(KMS) at different TS-content.

Figure 7. K and n change with TS-content.
Figure 7 shows K and n of five ADMs change with TS. K increases exponentially with the increase of TS, while n decreases linearly with the increase of TS. The rheological parameters model equations (11) and (12) of the five ADMs were obtained by curve fitting.

\[ K = a e^{bTS} \]  
\[ n = c + dTS \]  

Consistency coefficient K is as an exponential function of TS, because collision and friction of particles in the fluid increase strong with the increase of TS, which makes the consistency increase. At the same time, the water molecules are restrained in the network structure formed by the particles [26]. For straw suspension, K increased sharply with the increase of TS when TS-content greater than 4%. Value of n shows a linear decrease with the increase of TS, which is consistent with the fact that AD fluid which is the shear thinning fluid.

At the same TS-content, K value increased in the order of five ADMs which are low fiber manure, high fiber manure, straw manure mixture, straw suspension and digested sludge. The K value of straw suspension and digested sludge are always greater than the slurry of straw manure mixture, mainly due to the difference of fiber content. The larger the fiber content is, the larger the K value will be and the smaller n value will be [10]. The K value of cow manure and straw suspension was lower than that of pig manure and chicken manure, but the n value was opposite. It in accordance with the fact that a fluid with more fiber has a larger consistency and is more prone to shear thinning than a fluid with more starch.

4. Model application: A case for feed pump selection

4.1. Feed system of CSTR reactor

Figure 8 describes a feeding system of biogas plant with the volume of 6000m³ in Anhui province of China. The hydraulic residence time (HRT) of CSTR is 20 days and the TS-content of the feedings is of 4%-10%. Diameter of conveying pipe is 200mm; The premixed tank height \(Z_1\) and CSTR anaerobic reactor height \(Z_2\) are 7m and 20m respectively. Length of inlet pipe of pump \(\sum l_1\) and outlet pipe \(\sum l_2\) are 7m and 143m respectively; Atmospheric pressure \(P_0\) is 101.42KPa; The inlet and outlet pressure of the pump is \(P_1\) and \(P_2\) respectively. Both the local head loss coefficient of inlet pipeline \(\sum \xi_1\) and outlet pipeline \(\sum \xi_2\) are 15. The density of anaerobic fluid was calculated by \(\rho = 0.0367TS^3 - 2.38TS^2 + 14.6TS + 1000\) (kg/m³).

![Figure 8. Schematic of feed system using a pump to transport substrate from premixed tank to CSTR reactor.](image)

4.2. Fluid dynamics of the feed system

The AD fluid flowing in the tube can be regarded as a single homogeneous fluid. Bernoulli's equation was applied to calculate the pump head, outlet pressure and effective power in the feed system at the cross sections of position 0 and position 3. See equation (13), (14) and (15).
\[ H = (z_2 - z_1) + \frac{8Q^2}{g\pi^2D_1^4}(f_1 \sum \frac{l_1}{D_1} + \sum \xi_1) + \frac{8Q^2}{g\pi^2D_2^4}(f_2 \sum \frac{l_2}{D_2} + \sum \xi_2) + 0.5 \]  \tag{13}

\[ P_{outlet} = P_0 + \rho g z_2 + \frac{8Q^2}{\pi^2D_2^4}(f_2 \sum \frac{l_2}{D_2} + \sum \xi_2 - 1) \]  \tag{14}

\[ P_{effective} = H\rho gQ \]  \tag{15}

Where, \( f_1 \) and \( f_2 \) are friction loss coefficients along with the pipes respectively. \( \xi_1 \) and \( \xi_2 \) is local loss coefficient, respectively. The Volume flow rate and the velocity are calculated by equation (16) and (17):

\[ Q = \frac{V}{HRT} \]  \tag{16}

\[ u = \frac{4Q}{\pi D^2} \]  \tag{17}

For Non-Newtonian power-law fluids, friction factor \( f \) is a function of Reynolds number, where Reynolds number \( Re_{MR} \) is given by Metzner and Reed [27]:

\[ Re_{MR} = \frac{\rho u^2 - n D^n}{k(0.75 + 0.25/n)^{nB^{n-1}}} \]  \tag{18}

In the laminar flow, \( (Re_{MR}<2000) \), \( f \) can be defined as equation (14) through Blasius equation[28]:

\[ f = \frac{16}{Re_{MR}} \]  \tag{19}

4.3. Feed pump selection

According to the experience of biogas plant design, the procedure of feeding pump selection is as follows: firstly, the apparent viscosity of ADMs is determined according to the type of ADMs and TS-content; then, the type of pump according to the characteristics of the pump is selected; finally, the head, outlet pressure and effective power of the feeding pump are calculated according to the apparent viscosity.

For the biogas project with the volume of 6000 m³ in Anhui province in the feed system, in the condition of the flow rate of 50m³/h and pipe diameter of 200 mm, the apparent viscosity changes with TS-content (see Figure 9) according to the rheological parameter models of five clusters of ADMs is acquired. Influence of apparent viscosity of five clusters of ADMs on the feed pump head, the outlet pressure and the effective power (see Figure 10) were calculated. The apparent viscosity of ADMs is 15.60Pa·s inquired in Figure 9 when conveying stock and manure mixture with TS-content of 10%. The screw pump can be used for feed pump according to the comparison of properties of open centrifugal pump, screw pump and rotor pump when the diameter of ADMs is less than 15mm (see Table 2). At last, the pump head, effective power and the outlet pressure of the pump were 16.1m, 3.85kW and 0.48MPa obtained by figure 10.

5. Conclusions

Three conclusions were drawn in this work:

(1) ADMs can be divided into five categories: low cellulose manure, high cellulose manure, straw manure mixture, straw suspension, digested sludge. The models of rheological parameters of five clusters were carried out which K is as the exponential function of TS-content and n is as the linear function of TS-content with the TS-content of 4%-10%.

(2) The CH value was used to compare the results of hierarchical clustering method and k-means clustering method, and the K-means method is better for rheological parameters clustering.

(3) Models of five clusters can be applied in the pump selection in biogas plant.
Figure 9. Viscosity of five clustered anaerobic materials at TS-content from 4% to 10%.

Figure 10. Influence of pump head, pump effective power and pump outlet pressure changes with viscosity of 5 ADMs at TS-content of 4%, 6%, 8% and 10% (Q= 50m3/h and D=200mm).

Table 2. Performance comparison of single stage centrifugal pump, screw pump and rotor pump.

| Classes            | Viscosity | Outlet pressure | Flowrate | Head | Max Particle size | Max TS-content |
|--------------------|-----------|-----------------|----------|------|------------------|----------------|
| Open centrifugal   | 0-10      | 0-0.6           | 2-2600   | 2-50 | 2-3mm            | Less than 6%   |
| Screw pumpb        | 0-100     | 0-1.8           | 2-150    | 2-100| 16mm in Diameter,100mm in length | 40%-60%        |
| Rotor pumpc        | 0-100     | 0-1.8           | 1-3000   | 2-150| 70mm             | More than 40%  |

a. http://www.equanpump.com/equanpump Products-9650513/; b. http://www.hw-pump.com/Product/8423613329.html; c. http://www.luodebeng.com/tzrb/ldlzzb.html.

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