An improved batch fluidized drying experimental design based on digital sensors and a minicomputer

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Abstract
In most undergraduate programs of chemical engineering in Chinese universities, the batch fluidized bed drying (BFBD) experiment is commonly adopted as a part of the experimental course of chemical engineering unit operation. In those BFBD experiments, the students should dry the material in a dryer, repeatedly sample and measure it outside to get its moisture content. In most cases, each sampling and measuring operation needs more than 5 min. The BFBD drying experiment conducted in that manner cannot obtain adequate, accurate data, making it difficult for the student to perform proper calculation and data analysis. In this article, the authors build a small BFBD prototype equipment and mount a set of digital temperature/humidity sensors. Then they use a Raspberry Pi 3, a kind of mini-computer, to automatically measure and record the process parameters values online. Aided by those modern information process methods, the data accuracy and amount are all enhanced. Based on the gotten big data set, the student can get much more accurate results and do a more thorough analysis. The data analysis based on the old BFBD equipment is too straightforward and simple because it only needs the mass balance calculations. On the contrary, although the new BFBD equipment adopts an indirect way to measure the drying process, it obtains much more accurate results than before. The students must also apply more theories to get the results, such as mass transmission, the thermal balance, which makes the experiment more comprehensive. That is meaningful and helps to achieve the objectives of the chemical engineering experiments.

KEYWORDS
batch fluidized bed drying, chemical engineering experiment, mass balance, Raspberry Pi, transmission

1 | INTRODUCTION
In chemical engineering, unit operation is a basic component of the chemical process. Through theoretical lectures and laboratory experiments, typical unit operations such as separation, mass transmission, and heat exchange are taught in
chemical engineering education programs. In Chinese universities, these courses have names such as chemical engineering principles, unit operations, or transmission principles. The main teaching objective of laboratory experiments is to allow students to become familiar with the theoretical background, deeply understand the unit operations, and provide practice in solving real problems using their engineering knowledge.

As one of the typical unit operations, drying operations are widely used in industrial chemical processes. Thus, drying process experiments are an essential part of experimental courses, which usually include one or more different drying methods, such as fluidized bed drying, batch fluidized bed drying, and tunnel drying. Among these drying methods, fluidized bed drying experiments are commonly implemented because they are suitable for university laboratories.

Fluidized bed drying is an operation to remove water or a certain liquid-phase composition from granular solids such as grains, chemicals, pharmaceuticals, or minerals. The working mode of the fluidized bed can be either batch or continuous. Continuous systems are used for large-scale production, while batch dryers have applications for small-scale production.

In many university experimental laboratories, the typical structure of batch fluidized bed drying (BFBD) experimental equipment has been presented in the literature. To analyze the drying process, students should perform one or more entire drying processes using this equipment, and then describe the drying processes quantitatively and qualitatively. To achieve this goal, students should record necessary parameters including the moisture content of the dried material, temperatures of the material and gas, and gas flow rate. These parameters are then used to calculate the coefficient of the transmission rate, create the drying curve, calculate the drying rate, and determine the critical moisture content.

The temperature and air flow rate can be obtained easily with sensors or instruments. However, there is no way to measure the moisture content of the material continuously using the conventional equipment. Using that equipment, students must periodically remove a small amount of the wet material from the fluidized bed using a sampler via a fixed sample nozzle, and then immediately measure the moisture content of the sample. To accomplish this, an external rapid dryer, for example, an infrared dryer or oven, is often used. The weight of the sample is measured at the beginning and end of the external rapid drying process, and then its moisture content is calculated. Throughout the whole BFBD process, students will repeat the sampling and drying operations 10 or more times.

There are some obvious drawbacks to the conventional BFBD experimental method. Usually, it takes 5 min or more to complete a single sample measuring operation. Thus, the data set students can obtain from one BFBD process often includes less than 20 data points. After eliminating the data noise and performing some type of data cleaning, the data set is far from sufficient for a comprehensive and satisfactory analysis. An example has been reported showing the results for the drying curve and drying rate curve derived from a BFBD experimental data set. In that paper, the resulting curves contain only six data points, which is quite rough, and the students must thus make some assumptions and approximations.

Furthermore, because the sampling and measuring operations are exposed to the atmosphere, the sampled material likely exchanges water with the air. Because it is difficult to accurately measure these exchanges, noise is inevitably introduced into the data.

Besides the problems related to the acquisition of parameter values, the teaching objective of these experiments should also be discussed. When performing experiments using the conventional equipment, the process of data analysis and discussion after the parameter acquisition is simple and requires only a few mass balance calculations. Although the process involves both a mass balance and thermal balance, thermal transmission analysis cannot be performed because no temperature parameters are obtained. This means that the relevant transmission theories cannot be discussed effectively through these experiments, which limits the educational performance of the BFBD experimental unit. This should be improved by implementing new experimental and equipment designs.

According to the literature and our investigations, drying experiments are used in most of the relevant university laboratories in China. However, as described above, the experimental method has drawbacks and needs improvement in terms of both the experimental equipment and experimental methods.

In this article, the authors present a new design for BFBD experiments, avoiding the drawbacks mentioned above. The proposed BFBD experimental design uses digital sensors and information technology to make the experiment more efficient and comprehensive. Section 2 introduces the proposed BFBD equipment design and experimental operations. The new equipment also introduces new experimental methods. Section 3 describes the relevant data analysis and case studies. Finally, a summary and future directions are presented in Section 4.
NEW BFBD EXPERIMENTAL METHOD

2.1 Equipment design

Because data noise will be introduced by the sampling and external measurement operations in conventional BFBD experiments, it is desirable to develop a new method to measure the moisture content in the fluidized bed. An indirect measurement method will be more suitable.

There are measurement methods that can be used to obtain the moisture content of the material in a fluidized bed dryer. Pugsley introduced an approach for moisture measurement using electrical capacitance tomography (ECT) sensors. Zhang et al. used an electrostatic sensor array to obtain the inner moisture content. Lauri reported a soft sensor approach for moisture measurements in a batch fluidized bed dryer. Özahi employed a set of moisture probes to obtain the moisture content in their experimental setup. Beigi and Yogendrasasadhar introduced a method for measuring and calculating the moisture content based on the values obtained from two air humidity sensors.

Among these methods, considering the size of our equipment, the accuracy to be achieved, and the effort required for the measurement, we selected the latter method for the design of our batch fluidized bed dryer, which uses an indirect and continuous measurement method. The required parameter, that is, the moisture content, is calculated by recording the relative humidity (RH) of the outlet air. The calculation details are discussed in the next section.

The humidity sensor used has a small sampling delay of only a few seconds, thus allowing the sampling interval to be shortened significantly. As a result, the number of data points is much larger than in the conventional method, making the subsequent analysis much easier. On the other hand, the measurement is performed entirely inside the fluidized bed without sampling and external drying operations, which avoids the introduction of external data noise. The main drawbacks of the conventional BFBD method are eliminated by these improvements. The proposed BFBD prototype is shown in Figure 1.

The prototype fluidized bed is made of poly(methyl methacrylate) (PMMA), with a height of approximately 1 m and diameter of 4 cm. The material to be dried is composed of silica gel desiccant particles, which have been ground to an average diameter of approximately 1 mm.

The humidity sensor we selected is a model SHT15 manufactured by SENSIRION®, which is widely used in experiments and industry. The random noise of the humidity sensor is approximately 2%–4%. To improve the measurement accuracy, we mounted two identical humidity sensors on the top outlet of the fluidized bed. This is expected to reduce the random data noise level by half.

**FIGURE 1** Schematic of the proposed new BFBD equipment
If hot air is fed into the fluidized bed to desiccate the internal material, the humidity of the inlet air is also required to calculate the material moisture content; however, this will introduce additional data noise. Therefore, we used pure N₂ instead of air as the drying gas. Because the humidity of N₂ is approximately zero, there is no need to measure the humidity of the intake gas, thus completely eliminating this noise source.

The gas temperature at both the inlet and outlet is also needed for data analysis. Fortunately, the SHT15 sensors also have a temperature measurement capability, and thus this data can be collected together with the humidity data.

Before feeding into the fluidized bed, the N₂ flowrate and pressure should be read from the pressure meter and flowrate meter installed on the pipeline. Then, the N₂ is heated by a computer-controlled heater. The inlet N₂ temperature is controlled to be between 25°C and 50°C. After the N₂ passes through the fluidized bed and desiccates the material, its humidity will increase significantly. The humidity of the N₂ is measured by the two humidity sensors at the outlet. Then, the wet N₂ is released into the air. Although N₂ is harmless, there is an air vent installed above the equipment to exhaust the N₂.

2.2 Data acquisition

Throughout the drying process, certain process parameters, including the N₂ flowrate, pressure, and inlet temperature, will remain stable, and these are regarded as the drying process conditions. Students should manually record these in each process.

The wet outlet N₂ temperature and relative humidity are the main process parameters for the drying process. These will change continuously throughout the drying process. To describe the drying process, the students’ main job is to analyze the process using these parameters. The amount of data obtained depends primarily on the data recording speed. Therefore, to increase the amount of data, we developed an automatic data recorder that can acquire data much more frequently than humans.

The data source is the three SHT15 digital sensors. Obtaining data from these types of digital sensors usually requires a microcontroller-based unit (MCU)¹⁹,²⁰ or a personal computer (PC). However, MCUs usually do not have friendly user or communication interfaces, which often require a substantial amount of programming work. Moreover, installing a set of PCs is cumbersome, as their only task is data recording. After seeking an alternate choice, we found a suitable solution based on the Raspberry Pi®, which is extensively used in embedded intelligent devices today.²¹,²²

The Raspberry Pi® is actually a fully functional computer. It can be assembled in a box as small as a credit card and can provide almost all modern computer functions. It has all of the necessary hardware elements, such as a wireless network adapter (2.4G Wi-Fi), four USB ports, HDMI display ports, and the necessary general purpose I/O pins. It also has the required software environment, including Linux OS, a graphical user interface, the Python 2.7 programming language, a database server, and a web server. Even more, the data communication program module for the SHT15 sensor is available as an open source library. Thus, all we need to do is assemble them and perform a little software integration. After conducting some investigations, we finally adopted a Raspberry Pi® third generation as our automatic data recorder.

In our framework, the Raspberry Pi® 3 is configured as a standalone Wi-Fi hotspot with a running web server. To complete these steps, knowledge of the services and package installations in Linux is necessary. We used two service components to configure the Raspberry Pi as a Wi-Fi hotspot: hostapd and isc-dhcp-server, which can be easily installed using the package management called “apt” under Debian series Linux systems. We configured it as a Wi-Fi hotspot because we do not have a Wi-Fi connection in the laboratory. If the device can connect to an existing wireless network, there is no need for these configurations. Instead, connecting it to the wireless network and obtaining an IP address is sufficient.

We developed a web-based system running on a web server, similar to the scheme reported in the literature.²³,²⁴ The interfaces for controlling the data acquisition, displaying the data record history, and plotting the resulting data curves are all presented in a set of web pages. The users, including the teacher and students, can access the system when the wireless network environment is ready.

The interfaces and their connections to the data acquisition system are shown in Figure 2. The Raspberry Pi has a 40-pin GPIO (general purpose input/output) port that can be connected to other devices. The SHT15 sensor has a two-wire digital data communication interface using a private serial communication protocol. We used three pairs of pins to read values from the three sensors, and one pair of pins as the 3.3 V power supply for the sensor. The pin numbers are shown in Figure 2. For convenience of operation, we attached a small LCD monitor (model number LCD-1602) to the Raspberry Pi to display the sensors’ status. The monitor used two pins for I²C protocol communication and two pins for a 5 V power supply.
In the laboratory, students should connect to the Raspberry Pi® 3 via 2.4G Wi-Fi using their personal devices, such as smart phones, iPads, or laptop computers. They can scan the QR code pasted on the equipment or manually input the specific URL to access the system using their web browser and operate the equipment via the web pages.

Throughout the process, they can inspect the real-time parameter values online and preview the data curves. Finally, after completing the experiments, they can download the complete obtained data set in Excel® format for subsequent data analysis. The Raspberry Pi® 3 continues working in the background, recording all of the acquired data persistently in its MySQL database. For students, the data acquisition method is efficient, convenient, and less boring than the conventional method.

The student UI for data recording is a simple web page that contains two buttons to START/STOP data recording and a list of existing data sets. During the data recording process, the system presents the drying rate curve and dynamic drying curve. These can also be obtained after the experiment is completed. In Figure 3, the two data curves are shown.

Several different technologies can be used to implement these types of web-based applications. In the literature,23 Node.js has been adopted as an overall technology framework. In addition,24 the Apache web server and PHP programming language have been employed. Because Linux running on a Raspberry Pi is nearly a fully functional operating system, almost all of the relevant technologies can be used, such as Java, CGI, and Python. Of these, we are most familiar with Python and thus selected it as our overall technology framework. All of the software components we developed, including the data collection service, database access modules, and web server, were completed in the Python 2.7 programming language.

We used the Django framework to implement the web-oriented system. Django is a widely used Python web system framework that provides many basic system components. First, Django should be configured carefully to listen to the web on the network. When a user sends a request to the server, the Django framework distributes it to an appropriate program segment according to its configuration. Then, after the program completes the data processing, it collects the results, renders a view page, and returns it back to the user. The request, distribute, and response workflow is controlled by the Django framework, and thus developers can pay more attention to their own program segments to perform specific data processing tasks. The collected data are finally stored in the MySQL database server, which is a popular open-source database server supported by almost all platforms and programming languages.

Some third-party code libraries were imported into our system, which are shown as modules in Figure 4. These can complete general purpose functions, including database access, sensor communication, LCD monitor control, and data curve displays.

The main part of our software is web applications, including the functions of listing historical data, displaying current data, and controlling the sensor sampling. These are all independent program segments that are invoked by the Django framework when working. For example, the source code segments for the data displays are listed in the left part of Figure 5.
The source code segments are mapped to specific request URLs using the Django configuration. When the user clicks the specific URL link to display data, a request is sent to the server and invokes the program segment of the “display” function in Figure 5. It retrieves the data from the MySQL database using the object MySQLdb and the relevant data access functions, including connect(), cursor(), and execute(), which are provided in the Python MySQL library. Then, the program assembles a view page based on the retrieved data set in HTML format. The generated result page is directly written to the output stream of the HttpResponse object, supported by Django. Finally, the user obtains his or her result page in their web browser.

The values obtained from the sensors are collected by the data collection service written in Python. The service is a simple and independent program that runs as a thread. When the user clicks the START button, an internal status flag is set and the thread is activated, after which the thread will continue running until the status flag is reset by the user. The sensor value collection codes are listed in the right part of Figure 5. The data obtained will be stored in the database after one collection cycle, which will be repeated when the flag status is on. The object SHT1x and its functions, including _read_humidity() and read_temperature_C(), are provided by the third-party SHT library module.

The total hardware cost of the automatic data recorder is approximately US$100. The entire software environment is free. We developed the required program and have placed it on Github (https://github.com/mrcuill/Batch-Fluidized-Bed-Drying/).
3 | DATA ANALYSIS AND CASE STUDY

3.1 | Introduction to the experiment requirements

The analysis of fluidized bed drying, in both continuous mode and batch mode, has been presented in terms of various aspects. Makkawi introduced a mass transfer model for a bubble fluidized bed. Nazghelic introduced a method for the analysis of an industrial continuous fluidized bed from a thermodynamic perspective.
Özahi\textsuperscript{27} described a thermodynamic mode applied to a batch fluidized bed dryer. Ochsenbein also presented a heat–mass balance model of a pharmaceutical industrial continuous fluidized bed drying process.\textsuperscript{28} Wang,\textsuperscript{10} Beigi,\textsuperscript{15} and Srinivas\textsuperscript{9} presented heat and mass transfer models to describe the phenomena within the dried particles in a batch fluidized bed dryer. Because fluidized bed drying has been developed over many years, many of the corresponding models and related approaches have been employed in various applications.\textsuperscript{16,29-31} These thermodynamic models and mass transfer models deeply analyze the drying processes based on heat and mass transfer principles. Some models have focused on the micro scale of the particles, while others have focused more on the plant scale.

However, in our application, the main purpose of the laboratory experiment is to educate students on the principles of the drying process, and utilize their mass transfer and heat transfer knowledge to analyze the process. Performing a thorough and in-depth theoretical analysis may be excessively difficult for a second-year undergraduate. Therefore, the analysis and method we adopted are simplified to match the students’ knowledge level and prerequisite courses.

Based on our requirements, the main results the students should obtain are the drying curve, drying rate curve, and critical moisture content of the material. The drying curve describes the relationship between the moisture content and the time. The drying rate curve shows the moisture content versus the drying rate. The critical moisture content is a critical point existing in the drying rate curve that divides the drying process into two stages: desiccation of free water and desiccation of bound water. These results are related to each other and can be calculated from the outlet N\textsubscript{2} humidity if the experimental conditions are known.

During the calculation, students calculate the amount of water removed by the N\textsubscript{2}. Then, they calculate the moisture content of the material when the weight of the anhydrous material is given. Considering the time elapsed, the drying curve and the drying rate curve can also be derived from these data. These calculations are mainly based on the mass balance,\textsuperscript{24} and are relatively simple for an undergraduate chemical engineering student. However, this is only the first stage required for the analysis of the experimental data.

Because the temperatures of the inlet N\textsubscript{2} and outlet N\textsubscript{2} of the fluidized bed are also known, data analysis can also be performed based on the thermal balance.\textsuperscript{26} This is more complex because the given and acquired data are insufficient and additional knowledge is required. Students may have to make some assumptions and approximations.

Finally, the students should compare the results calculated from the mass balance and thermal balance, and then analyze the results to obtain their conclusions.

The given parameters of the experimental conditions are listed below.

\begin{itemize}
  \item $T_0$ (°C): temperature of the environment;
  \item $P_{gage}$ (bar, gage): N\textsubscript{2} pressure just before feeding into the flow meter;
  \item $F_v$ (L/min): flowrate of the N\textsubscript{2} given by the flow meter, volume flowrate;
  \item $M_b$ (g): weight of the anhydrous material;
  \item $M_{in}$ (g): mass of water injected into the dry material before drying.
\end{itemize}

The acquired parameters are listed below.

\begin{itemize}
  \item $t_k$ (ms): time point of the $k$th sampling operation;
  \item $T_{in}$ (°C): temperature of the N\textsubscript{2} in the fluidized bed inlet pipeline;
  \item $T_{out}$ (°C): temperature of the N\textsubscript{2} in the fluidized bed outlet, mean value of the two sensors;
  \item $RH$ (%): relative humidity of the N\textsubscript{2} in the fluidized bed outlet, mean value of the two sensors.
\end{itemize}

Student will note that not every parameter can be measured perfectly. In addition to the humidity sensor data noise discussed above, the inlet N\textsubscript{2} temperature also has a deviation. Although the inlet N\textsubscript{2} temperature is controlled by an automatic gas heater, the actual temperature is still somewhat unstable, with a fluctuation of approximately 2° C. Furthermore, there is no space or port at the bottom of the fluidized bed for a temperature sensor, and the pipeline is too thin to install an inner sensor. Thus, it is necessary to attach a sensor to the surface of the inlet pipe and install some heat insulation treatment around it. Although the pipeline is composed of steel and the thermal conductivity is relatively good, there is still data deviation, which means the sensor value is not equal to the actual value. Some assumptions and data corrections are thus required.

Using the data listed above, the simplified calculation processes based on the mass balance and thermal balance are described below.
### 3.2 Calculation based on the mass balance

The N$_2$ volume flowrate at environment temperature $T_0$ is as follows:

$$F_{v0} = F_v \cdot \sqrt{\frac{\rho_{\text{air}}}{\rho_{\text{N}_2}}} \cdot \sqrt{\frac{P_{\text{N}_2}}{P_{\text{std}}}} \cdot \frac{T_{\text{std}}}{T_{\text{N}_2}} \quad (L/\text{min}),$$  

(1)

where

- $\rho_{\text{air}} = 1.25$ is the density of air at 273.15 K and 1 atm (kg/m$^3$);
- $\rho_{\text{N}_2} = 1.29$ is the density of N$_2$ at 273.15 K and 1 atm (kg/m$^3$);
- $P_{\text{N}_2} = P_{\text{gage}} \times 10^5 + 101,325$ is the pressure of N$_2$ in the flowmeter (Pa);
- $P_{\text{std}} = 101,325$ is the standard pressure during the flowmeter calibration (Pa);
- $T_{\text{std}} = 293.15$ is the standard temperature during the flowmeter calibration (K); and
- $T_{\text{N}_2} = T_0 + 273.15$ is the temperature of the N$_2$ (K).

The corresponding mass flowrate of the N$_2$ is as follows:

$$F_m = F_{v0} \cdot \rho_{\text{N}_2} \cdot \frac{T_{\text{N}_2}}{T_{\text{std}}} \quad (g/\text{min}).$$  

(2)

The mass flowrate of the water content is:

$$F_{\text{water}} = \frac{C_{\text{H}_2\text{O}} \cdot RH \cdot P_s}{C_{\text{N}_2} \left( P_{\text{atm}} - RH \cdot P_s \right)} \cdot F_m \quad (g/\text{min}).$$  

(3)

where

- $P_s$ is the saturated vapor pressure of water at temperature $T_{\text{out}}$, which can be found in the water vapor pressure data table (Pa);
- $C_{\text{H}_2\text{O}} = 18$ is the molecular weight of water;
- $C_{\text{N}_2} = 28$ is the molecular weight of N$_2$;
- $P_{\text{atm}} = 101.325$ is the atmospheric pressure (Pa); and
- $F_m$ is the mass flowrate of the gas phase, which is approximately equal to the mass flowrate of N$_2$.

As the humidity and temperature change gradually, we adopt a trapezoidal approximation to fit the humidity change curve. In other words, we assume that the humidity and temperature changes between two adjacent sample points are linear. Therefore, the water removed in the $k$th sample interval should be the following:

$$M_{\text{wloss}} (k) = F_{\text{water}}(k) \cdot (t_k - t_{k-1}) \quad (g).$$  

(4)

At the $k$th sample point, the moisture content should be:

$$C (k) = \frac{\left( M_{\text{in}} - \sum_{n=0}^{k} M_{\text{wloss}} (n) \right)}{M_b} \quad \text{(ratio)}.$$

(5)

At that point, the drying rate is as follows:

$$V_k = M_{\text{wloss}} (k) / (t_k - t_{k-1}) \quad (g/\text{min}).$$

The original data set in the case study has three drying process records. Each drying process required more than 40 min to complete, and the data recorder read the sensors every 3 s. These are the actual experimental results obtained on June 14, 2016, by a student group. In the end, they obtained three data sets containing approximately 1000 data points, which are too big to be shown here. Therefore, in Table 1, all of the data sets are simplified, and data points recorded at 2 min intervals are extracted for display. These three processes were carried out under different drying conditions, including different N$_2$ flowrates and temperatures, as summarized in Table 1. Only result set 1 is listed in Table 2.
| Time (min) | Process 1 | Process 1 | Process 1 |
|-----------|-----------|-----------|-----------|
|           | $T = 44^\circ C, F = 8.2$ L/min | $T = 44^\circ C, F = 9.6$ L/min | $T = 52^\circ C, F = 9.6$ L/min |
|           | $T_{in}$ (°C) | $T_{out}$ (°C) | RH (%) | $T_{in}$ (°C) | $T_{out}$ (°C) | RH (%) | $T_{in}$ (°C) | $T_{out}$ (°C) | RH (%) |
| 0         | 21.7       | 22.1       | 26.0       | 24.8       | 28.1       | 34.1       | 25.4       | 29.4       | 26.2       |
| 2         | 28.6       | 21.8       | 36.9       | 42.8       | 26.5       | 60.8       | 45.5       | 27.6       | 58.6       |
| 4         | 35.5       | 21.4       | 51.4       | 44.5       | 25.0       | 68.4       | 48.9       | 26.5       | 69.4       |
| 6         | 37.8       | 21.7       | 63.7       | 44.1       | 24.9       | 63.0       | 49.0       | 26.6       | 64.2       |
| 8         | 39.5       | 21.7       | 70.4       | 44.0       | 25.1       | 60.0       | 49.5       | 27.0       | 60.7       |
| 10        | 40.8       | 22.0       | 65.2       | 44.0       | 25.4       | 54.8       | 50.2       | 27.8       | 52.8       |
| 12        | 41.2       | 22.5       | 63.7       | 44.0       | 26.1       | 45.7       | 50.5       | 29.3       | 37.3       |
| 14        | 42.0       | 22.9       | 61.6       | 44.6       | 27.5       | 52.2       | 50.7       | 31.5       | 21.4       |
| 16        | 42.7       | 23.4       | 59.1       | 45.0       | 29.1       | 20.1       | 51.1       | 33.8       | 11.8       |
| 18        | 41.6       | 23.9       | 54.0       | 44.3       | 30.7       | 12.4       | 50.8       | 35.8       | 6.7        |
| 20        | 42.7       | 24.5       | 46.0       | 43.9       | 32.1       | 7.6        | 51.3       | 37.0       | 4.2        |
| 22        | 43.3       | 25.5       | 36.5       | 44.1       | 33.1       | 5.2        | 52.0       | 38.3       | 2.7        |
| 24        | 43.3       | 26.7       | 26.1       | 44.6       | 33.8       | 3.7        | 51.4       | 39.3       | 1.8        |
| 26        | 43.1       | 28.0       | 17.9       | 44.6       | 34.4       | 2.6        | 52.1       | 39.8       | 1.3        |
| 28        | 42.4       | 29.3       | 12.2       | 43.7       | 34.9       | 1.9        | 51.5       | 40.6       | 0.9        |
| 30        | 41.7       | 30.2       | 8.5        | 44.5       | 35.4       | 1.5        | 52.1       | 41.0       | 0.7        |
| 32        | 42.8       | 31.0       | 6.3        | 45.0       | 35.9       | 1.1        | 52.2       | 41.4       | 0.5        |
| 34        | 43.3       | 31.7       | 4.7        | 44.2       | 35.9       | 0.8        | 52.2       | 41.7       | 0.3        |
| 36        | 43.5       | 32.2       | 3.6        | 44.0       | 35.9       | 0.6        | 52.7       | 42.1       | 0.3        |
| 38        | 43.2       | 32.9       | 2.8        | 44.3       | 36.1       | 0.5        | 52.4       | 42.1       | 0.2        |
| 40        | 43.4       | 33.2       | 2.3        | 44.6       | 36.3       | 0.4        |            |            |            |
| 42        | 43.7       | 33.6       | 1.8        | 44.2       | 36.6       | 0.3        |            |            |            |
| 44        | 43.5       | 33.9       | 1.5        | 44.1       | 36.6       | 0.2        |            |            |            |
| 46        | 42.9       | 34.1       | 1.2        |            |            |            |            |            |            |
| 48        | 43.1       | 34.1       | 1.0        |            |            |            |            |            |            |

The result curves for these three processes are shown in Figure 6. The curves are generated from the complete data sets containing 800–1000 points each. Because the data points are close to each other, no fitting or smoothing post-processing is applied.

Comparing the experimental drying rate curve with the theoretical drying curves shown in Figure 7 indicates that the results are in good agreement. According to the theory, the critical value of the moisture content can be determined from the drying rate curve. The critical value should be approximately 0.12.

### 3.3 Results based on the thermal balance and comparison of the two methods

The thermal balance is dynamic because water is continuously removed from the equipment. We take Process 1 as discussed above as a case study for these calculations. In one sampling period of approximately 3 s, we can study the thermal balance and list the related linear equations. As the values change slowly, we also simplify this calculation using the trapezoid approximation.
### TABLE 2  Results of Process 1

| Time (min) | $T_{in}$ (°C) | $T_{out}$ (°C) | RH (%) | $P_s$ (kPa) | $F_{water}$ (g/min) | $M_{loss}$ (g) | $C$ | $V$ (g/min) |
|------------|---------------|----------------|--------|-------------|-------------------|--------------|----|----------|
| 0          | 21.7          | 22.1           | 26.0   | 2.661       | 0.079             | 0.003        | 0.355 | 0.079   |
| 2          | 28.6          | 21.8           | 36.9   | 2.616       | 0.106             | 0.188        | 0.341 | 0.106   |
| 4          | 35.5          | 21.4           | 51.4   | 2.562       | 0.146             | 0.442        | 0.321 | 0.146   |
| 6          | 37.8          | 21.7           | 63.7   | 2.599       | 0.184             | 0.780        | 0.295 | 0.184   |
| 8          | 39.5          | 21.7           | 70.4   | 2.599       | 0.203             | 1.154        | 0.267 | 0.203   |
| 10         | 40.8          | 22.0           | 65.2   | 2.641       | 0.191             | 1.555        | 0.236 | 0.191   |
| 12         | 41.2          | 22.5           | 63.7   | 2.723       | 0.192             | 1.937        | 0.206 | 0.192   |
| 14         | 42.0          | 22.9           | 61.6   | 2.787       | 0.191             | 2.325        | 0.177 | 0.191   |
| 16         | 42.7          | 23.4           | 59.1   | 2.867       | 0.188             | 2.701        | 0.148 | 0.188   |
| 18         | 41.6          | 23.9           | 54.0   | 2.948       | 0.176             | 3.065        | 0.120 | 0.176   |
| 20         | 42.7          | 24.5           | 46.0   | 3.067       | 0.156             | 3.404        | 0.094 | 0.156   |
| 22         | 43.3          | 25.5           | 36.5   | 3.254       | 0.131             | 3.690        | 0.072 | 0.131   |
| 24         | 43.3          | 26.7           | 26.1   | 3.491       | 0.100             | 3.918        | 0.054 | 0.100   |
| 26         | 43.1          | 28.0           | 17.9   | 3.773       | 0.074             | 4.091        | 0.041 | 0.074   |
| 28         | 42.4          | 29.3           | 12.2   | 4.076       | 0.054             | 4.221        | 0.031 | 0.054   |
| 30         | 41.7          | 30.2           | 8.5    | 4.304       | 0.040             | 4.314        | 0.024 | 0.040   |
| 32         | 42.8          | 31.0           | 6.3    | 4.505       | 0.031             | 4.383        | 0.018 | 0.031   |
| 34         | 43.3          | 31.7           | 4.7    | 4.689       | 0.024             | 4.438        | 0.014 | 0.024   |
| 36         | 43.5          | 32.2           | 3.6    | 4.833       | 0.019             | 4.481        | 0.011 | 0.019   |
| 38         | 43.2          | 32.9           | 2.8    | 5.015       | 0.015             | 4.515        | 0.008 | 0.015   |
| 40         | 43.4          | 33.2           | 2.3    | 5.098       | 0.013             | 4.542        | 0.006 | 0.013   |
| 42         | 43.7          | 33.6           | 1.8    | 5.209       | 0.010             | 4.565        | 0.004 | 0.010   |
| 44         | 43.5          | 33.9           | 1.5    | 5.300       | 0.009             | 4.584        | 0.003 | 0.009   |
| 46         | 42.9          | 34.1           | 1.2    | 5.373       | 0.007             | 4.599        | 0.002 | 0.007   |
| 48         | 43.1          | 34.1           | 1.0    | 5.358       | 0.006             | 4.611        | 0.001 | 0.006   |

### FIGURE 6  Results calculated with the mass balance method

![Graph showing moisture content over time for different settings](image-url)
The thermal balance within one sampling period can be represented as follows:

\[ Q_1 + Q_2 + Q_3 + Q_4 = 0 \]

where \( Q_1 \) is the heat released by hot \( \text{N}_2 \).

\[ Q_1 = F_m \cdot t \cdot C_p \cdot (T_{\text{out}} - T'_{\text{in}}) \quad (\text{J}), \tag{6} \]

where

- \( F_m \) is the mass flowrate of \( \text{N}_2 \) discussed above (g/min);
- \( T'_{\text{in}} = T_{\text{in}} + T' \) is the actual temperature feed in the equipment (K);
- \( C_p \) is the heat capacity of \( \text{N}_2 \) at atmospheric pressure (J/g); and
- \( t \) is the time of one sample period (s).

The calculation of \( Q_1 \) seems simple, but there is a problem in that \( T_{\text{in}} \) cannot be measured accurately because the temperature sensor does not contact the \( \text{N}_2 \), but is rather attached to the steel gas pipeline, as shown in Figure 8. Therefore, there will be a temperature deviation with an unknown value, represented by \( T' \). The \( \text{N}_2 \) temperature is controlled by a heater; we can assume that \( T_{\text{in}} \) and \( T' \) are stable in most stages of the process, and the value of \( T' \) is linearly related to \( T_{\text{in}} \). We can iterate its value at the end.

\( Q_2 \) is the heat required by water evaporation in one sample period.

\[ Q_2 = (2500.7 - 2.3688 \cdot T_{\text{out}} - 4.18 \cdot T_{g0}) \cdot M_{\text{water}} \quad (\text{J}), \tag{7} \]
where

\[ T_{g0} \] is the \( N_2 \) temperature at the phase interface between the gas and water/solid on the particle surface, which is unknown and should also be iterated \((K)\); and

\[ M_{\text{wloss}} \] is the weight of the removed water in one sample period \((g)\).

\( Q_3 \) is the heat absorbed by the wet material, including the water in the liquid phase and the silica gel desiccant particles.

\[
Q_3 = \left( C_{\text{Psilica}} \cdot M_b + 4.18 \cdot M_{wR} \right) \cdot \Delta T_{g0} \tag{8}
\]

where

\[ C_{\text{Psilica}} = 0.92 \text{J/g} \] is the heat capacity of the silica gel desiccant particles;

\[ M_b = 13 \text{g} \] is the weight of the dry silica particles;

\[ M_{wR} \] is the weight of the water left in the BFBD at the end of the current sample period \((g)\); and

\[ \Delta T_{g0} \] is the change in \( T_{g0} \) in the current sample period \(\circ\text{C}\).

\( Q_4 \) is the heat dissipation of the fluidized bed. To calculate this, the temperature distribution in the fluidized bed must be known. However, we only know \( T_{in}, T_{out}, \) and \( T_0 \). According to the rules of heat transmission in the solid equipment shell and free convection heat transmission in air, we can establish the equations for \( T_{out}, T_0, \) and the heat dissipation power, \( P_d \). Then, using the \( N_2 \) flowrate and its physical properties, we can set up a differential equation for the vertical position, \( H \), and temperature, \( T_x \). Although this seems solvable, unfortunately obtaining the analytical solution to these nonlinear equations is a significant challenge for a second-year undergraduate.

Therefore, under the experimental conditions, we employ some reasonable assumptions to make appropriate approximations and simplifications. The BFBD temperatures—\( T_{g0}, T_{avg}, \) and \( T_{out} \)—are assumed to have a linear relationship. The heat dissipation from the internal gas to the environment is simplified as stable and has a linear relationship with \( T_{avg} \). Therefore \( Q_4 \) can be obtained as follows:

\[
Q_4 = (T_{avg} - T_0) \cdot K \cdot t = \left[ \frac{T_{out} + T_{g0}}{2} - T_0 \right] \cdot K \cdot t \tag{9}
\]

where \( K \) is an equivalent comprehensive heat transmission coefficient.

Then, there are three unknown variables in the above equations: \( T_{g0} \) in Equations (7), (8), and (9), \( T_{in} \) in Equation (6), and \( K \) in Equation (9). Some principles and boundary conditions are used to iterate these values.

The amount of water lost should be equal to the initial amount of water, and \( Q_2 \) and \( Q_3 \) will be zero at the end of the process because there is almost no water left in the particles at that time. These boundary conditions can be used to iterate the unknown coefficient \( K \) in Equation (9). According to the data recorded, \( K \) is equal to 0.2315.

After the \( N_2 \) leaves the particle surface, its temperature will decrease from \( T_{g0} \) to \( T_{out} \). We assume that the heat dissipation process is linear, and thus the trend of \( T_{g0} \) should be similar to that of \( T_{out} \). We also assume that \( T_{g0} \) and \( T_{out} \) are equal to the environmental temperature at the beginning of the process, and \( T_{g0} \) is equal to \( T'_{in} \) at the end of the process because there is almost no water left and the system temperatures are all constant. Therefore, based on these assumptions, the trends of \( T_{in}, T'_{in}, T_{g0}, \) and \( T_{out} \) are shown in Figure 9. The values of \( T_{g0} \) and \( T'_{in} \) can be represented by the maximum value of the inlet temperature deviation, \( T'_{\text{max}} \).

**Figure 9** Trends in the \( N_2 \) temperatures
At the end of the process, the drying speed and amount of water remaining should decrease to zero concurrently; in other words, the drying speed curve should eventually reach the zero point. This boundary condition can be used to iterate the final unknown parameter, $T_{\text{max}}$. According to the data set, the value is 6.95.

The final result is shown in Table 3, and the curves are shown in Figure 10. These results are consistent with the curves calculated using the mass balance method shown in Figure 6. Some numerical results, such as the critical point and the maximum drying rate, are also quite similar.

Considering that we made some assumptions and approximations in the calculations, the results are acceptable. The main purpose of the thermodynamic data analysis is to allow the students to find solutions to resolve real and nonideal problems. During this process, because the known data are insufficient, students have to apply their knowledge of mass balance, thermal balance, and heat transmission concepts comprehensively. Some common data processing methods, such as data approximation and fitting, are also practiced. Although the final result is not very accurate, the objective of the analysis is achieved.

### Table 3  Calculation results for the thermal balance method

| Time (min) | $T_{\text{out}}$ (°C) | $T_{\text{in}}$ (°C) | $T_{\text{gb}}$ (°C) | $Q_1$ (J) | $Q_2$ (J) | $Q_3$ (J) | $M_{\text{wLGS}}$ (g) | $M_{\text{wR}}$ (g) | Moisture, g/g (ratio) | Drying speed (g/min) |
|------------|-----------------------|-----------------------|----------------------|-----------|-----------|-----------|-----------------------|----------------------|-----------------------|----------------------|
| 2          | 21.8                  | 30.8                  | 21.0                 | -335.1    | 11.6      | -105.3    | 428.8                 | 0.182                | 4.568                 | 0.35                 | 0.090                 |
| 4          | 21.4                  | 39.9                  | 20.2                 | -691.8    | -5.7      | 29.1      | 668.4                 | 0.283                | 4.323                 | 0.33                 | 0.139                 |
| 6          | 21.7                  | 42.9                  | 20.8                 | -788.2    | 6.4       | 27.8      | 754.0                 | 0.319                | 4.003                 | 0.31                 | 0.159                 |
| 8          | 21.7                  | 45.2                  | 20.7                 | -879.4    | 6.2       | -26.4     | 899.6                 | 0.381                | 3.663                 | 0.28                 | 0.188                 |
| 10         | 22.0                  | 46.9                  | 21.4                 | -928.1    | 19.6      | 37.3      | 871.1                 | 0.369                | 3.282                 | 0.25                 | 0.183                 |
| 12         | 22.5                  | 47.5                  | 22.7                 | -927.4    | 44.6      | 35.1      | 847.7                 | 0.360                | 2.920                 | 0.22                 | 0.179                 |
| 14         | 22.9                  | 48.5                  | 23.6                 | -959.8    | 64.3      | 54.8      | 840.7                 | 0.358                | 2.549                 | 0.20                 | 0.176                 |
| 16         | 23.4                  | 49.5                  | 24.8                 | -969.6    | 86.5      | 20.5      | 862.7                 | 0.368                | 2.187                 | 0.17                 | 0.183                 |
| 18         | 23.9                  | 48.0                  | 25.9                 | -902.7    | 109.5     | 28.6      | 764.6                 | 0.327                | 1.849                 | 0.14                 | 0.161                 |
| 20         | 24.5                  | 49.5                  | 27.5                 | -935.0    | 141.7     | 35.5      | 757.8                 | 0.326                | 1.521                 | 0.12                 | 0.160                 |
| 22         | 25.5                  | 50.2                  | 29.8                 | -924.5    | 188.9     | 74.3      | 661.3                 | 0.286                | 1.214                 | 0.09                 | 0.140                 |
| 24         | 26.7                  | 50.3                  | 32.6                 | -893.3    | 247.7     | 61.8      | 583.9                 | 0.254                | 0.954                 | 0.07                 | 0.124                 |
| 26         | 28.0                  | 50.0                  | 35.7                 | -821.6    | 306.3     | 51.0      | 464.3                 | 0.203                | 0.737                 | 0.06                 | 0.100                 |
| 28         | 29.3                  | 49.0                  | 38.8                 | -733.2    | 365.5     | 48.4      | 319.3                 | 0.141                | 0.557                 | 0.04                 | 0.070                 |
| 30         | 30.2                  | 48.1                  | 41.0                 | -662.7    | 408.8     | 60.0      | 194.0                 | 0.086                | 0.438                 | 0.03                 | 0.043                 |
| 32         | 31.0                  | 49.6                  | 42.9                 | -697.4    | 451.2     | 19.4      | 226.9                 | 0.101                | 0.331                 | 0.03                 | 0.050                 |
| 34         | 31.7                  | 50.3                  | 44.5                 | -692.0    | 479.8     | -69.1     | 281.4                 | 0.126                | 0.246                 | 0.02                 | 0.062                 |
| 36         | 32.2                  | 50.5                  | 45.8                 | -678.9    | 504.6     | 18.4      | 155.9                 | 0.070                | 0.172                 | 0.01                 | 0.035                 |
| 38         | 32.9                  | 50.2                  | 47.3                 | -641.9    | 534.1     | 18.0      | 89.8                  | 0.040                | 0.113                 | 0.01                 | 0.020                 |
| 40         | 33.2                  | 50.3                  | 48.0                 | -644.9    | 554.6     | -11.8     | 102.2                 | 0.046                | 0.070                 | 0.01                 | 0.023                 |
| 42         | 33.6                  | 50.8                  | 48.9                 | -656.2    | 580.0     | 17.6      | 58.7                  | 0.026                | 0.041                 | 0.00                 | 0.013                 |
| 44         | 33.9                  | 50.6                  | 49.6                 | -626.2    | 586.0     | -23.3     | 63.6                  | 0.029                | 0.021                 | 0.00                 | 0.014                 |
| 46         | 34.1                  | 49.7                  | 50.2                 | -581.4    | 592.6     | -17.4     | 6.2                   | 0.003                | 0.013                 | 0.00                 | 0.001                 |
| 48         | 34.1                  | 50.0                  | 50.1                 | -594.9    | 592.1     | 52.2      | -49.4                 | -0.022               | 0.015                 | 0.00                 | -0.011                |

### 3.4 Changes produced by the large data set

The traditional BFBD experimental data analysis requires many assumptions and approximations because the obtained data are insufficient owing to limitations of the experimental technologies and methods. In the case shown in the first
section, the student can obtain only about 10 data points. Based on such a small data set with unknown data noise, it is almost impossible to fit the results to a theoretical drying rate curve having four stages. The accuracy and reliability of the results cannot be guaranteed.

However, aided by modern sensor and information technology, data acquisition is much easier than before. In our new BFDB experimental setup, the automatic data recorder can read all of the sensors every 3 s. Using such equipment, students can obtain 700–1500 data points in one drying process, depending on the experimental conditions. With such a large data set, the data analysis processes will be slightly different.

The random data noise can now be easily suppressed by some simple data processing methods because the sample set is sufficiently large. Even a simple moving average method can achieve quite good results. In other words, big data not only increases the data quantity, but also improves the data quality.

Moreover, owing to data noise and nonideal experimental conditions, a bias of the experimental data from the ideal case always exists. If the data points are insufficient, the students have to decide, and maybe guess, how to balance the effects of the noise with those of the nonideal conditions. In the new method, after largely suppressing the random data noise, students can focus on the effects of nonideal conditions, which is sometimes the main goal of the experiment.

The drying rate curve is one of the main results of the drying experiment, and it has at least two critical points in theory. Using the conventional BFBD equipment, limited by the number of data points, students must first refer to the theoretical curve to assume the locations of the critical points, and then they can apply linear interpolation based on this assumption. However, under different experimental conditions, the theoretical curve will also differ. In other words, this assumption is probably incorrect.

Currently, with new BFBD equipment, the data points are so dense that students can obtain a fairly smooth curve by simply connecting the raw data points, as shown in Figure 5. The trends in the data are obvious, and the typical theoretical curve is apparent. The critical points can thus be determined more easily. The importance of assumptions is decreased significantly. Therefore, the data analysis results are improved in terms of both accuracy and reliability.

Furthermore, aided by the large data set, students can discover some direct relationships between the physical phenomena and changes in the data curve, which cannot be represented in the conventional experimental data analysis. In one instance, the air distribution plate at the bottom of the fluidized bed flipped, resulting in an unstable and uneven N₂ flow until the end of the experiment. That event was represented in the data curve, as after that time point the drying rate became very unstable. For another example, at the beginning of each drying process, as the material is wet, it often agglomerates and results in bypassing of the N₂ flow. The students must frequently strike the fluidized bed gently to vibrate the material and prevent bypassing. These operations can also be observed in the data curves as random distributions of data. The data curves usually vibrate strongly at the beginning. Then, after a certain time point, at which the N₂ can blow through the particles without agglomeration, the curve becomes stable. In addition, the level of data vibration depends on the frequency and strength of the manual strikes.
4 | SUMMARY AND FUTURE WORK

The authors’ studies are mainly aimed at chemical engineering education and the corresponding experimental courses, and the main purpose of this study is to improve the performance of BFBD experiments.

Aided by modern sensors and information technology, the new BFBD equipment can acquire data automatically and continuously at a stable frequency. The time required for data recording is thus greatly reduced. This not only releases the students from dull manual tasks, but also significantly improves the data quality. The analysis based on the improved data set can result in more accurate and reliable results, while also helping students avoid incorrect assumptions.

Owing to the change in the experimental method, the requirements for the data analysis increase. Students must use mass transfer, heat transfer, and other mathematical methods to analyze the data, thus changing the experiment from a simple mass transfer experiment to a comprehensive experiment. During the data analysis, some engineering methods, such as approximation and simplifications, should also be applied, which makes the experiment much more challenging and interesting.

The current BFBD prototype equipment was modified from research equipment. Therefore, in the immediate future, we will design new BFBD equipment based on the prototype. More sensors will also be mounted on the new equipment. For example, some pressure sensors will be added to measure the fluidized bed pressure change to calculate the performance of the fluidization.

Finally, because the Raspberry Pi has achieved quite successful applications in data acquisition with the advantages of intelligence, high efficiency, compactness, and power savings, we plan to use it to replace most of the computer-based data acquisition systems in our experimental center. This method is also applicable for most data collection and simple control scenarios in the laboratory, even in industry. However, the Raspberry Pi is only a laboratory-level product and has some limitations, such as the lack of an A/D converter, poor heat dissipation capacity, and insufficient stability for long working times. If someone wanted to apply this method in more severe conditions, other industrial-grade devices may be more suitable, such as the Beagle Bone® series devices, which are very similar to the Raspberry Pi for developers and users.

PEER REVIEW INFORMATION
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DATA AVAILABILITY STATEMENT
The data that support the findings of this study are openly available in GitHub at https://github.com/mrcuilin/Batch-Fluidized-Bed-Drying/.

CONFLICT OF INTEREST
The authors have no conflict of interest relevant to this article.

AUTHOR CONTRIBUTIONS
Lin Cui lead the conceptualization, data curation, formal analysis, software, writing—original draft and equally contributed to the methodology. Yong Peng equally contributed to the investigation, methodology, and supervision. Li Ding supported the methodology and resources. Diannan Lu, equally contributed to the project administration, supervision, and validation.

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