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Comparison of Conventional and Vibration Assisted Fluidized Bed Dryer for Drying High Moisture Sub Bituminous Coal Used in Thermal Power Plants

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Abstract: Low Calorific Value (CV) coal is used in large quantity as compared to High Calorific Value coal in Cogeneration Power Plant (CPP) at Gayatrishakti Paper & Board Limited Unit-1, Vapi. But the moisture content in Low CV coal is very high about 35% - 45% (wet basis) which is not acceptable due to sticky property of coal, hence leads to increase in operation and maintenance costs attributed to handling of wet coal. So drying of coal is necessary to use Low CV. The drying performance of Low CV coal particle in laboratory scale with and without vibration assisted fluidized bed dryer was investigated under various operating condition: Inlet air temperature (60 - 80℃), superficial air velocity (0.14 – 0.43 m/s), bed height (20-60 mm), particle size (1-2,2-3,3-5 mm), frequency (110 - 340 Hz). The drying results shows that the moisture content with respect to time decreases with an increase in temperature, air velocity, and vibration frequency, and also increases with an increase in bed height and particle size.

Keywords: Low-rank coal, Fluidized Bed Technology, Coal Drying, Vibration Technology.

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1. Introduction

The coal used in Thermal Power Plant at Gayatrishakti Paper And Board Limited, Unit-1, Vapi for steam generation is Imported Coal categorized as Low and High Calorific Value Coal (5400 GCV to 6000 GCV, dry basis). In the last two years, there is a large increase in the price of Imported coal which lead to the unavailability of High CV coal and running thermal power plants, with 100% Low CV coal having moisture content (35 to 45%, wet basis). This leads to low heating value, and lower thermal efficiency in combustion [1]. Reduced boiler efficiency and reduced total unit efficiency will result in an increase in operating expenses (increase in heat rate), due to the handling of wet coal, operating and maintenance expenses have increased. However, coal procurement costs have decreased because of greater moisture levels and lower GCV. [4]. this property limits LRC from being widely used. [2, 3].

Low-rank coal (LRC) or Low calorific value (Low CV) coal includes lignite and sub-bituminous coal. High calorific value (High CV) coal Include Bituminous and Anthracite.

There are many technology available to dry Low CV coal such as Conventional Evaporative Dryers, Superheated Steam Dryer, Screw Conveyor Dryer (SCD), Microwave Drying, Impinging Stream Drying (ISD), Novel Fluidized Bed Dryer, Renewable Sources of Energy for Coal Drying, Use of Waste Heat, Use of Coal Mine Methane, Processing of LRC prior to drying, Displacement drying of coal [5-8]. Out of this technology fluidized bed dryer can be implemented for drying low CV coal used in thermal power plant.

1.1 What is coal?

The storage of energy in the form of preserved plant material is represented by coal, a solid fossil hydrocarbon. As a result of the preservation process, the plants have been reduced to organic matter, which consists of moisture, ash, volatile matter (gases and liquids released during heating), and fixed carbon. Energy is released when coal is burned, and both the fixed carbon and volatile matter contain energy.

Coal is one of the main energy sources in the world, which is used as fuel for power plant Therefore, it is still considered as an important sources due to it's cheap in price compared to other fossil fuel and spread in some countries as energy reserves.

Generally coal is classified into the category of Peat, lignite, sub-bituminous, bituminous, Anthracite.

Peat: Peat is not generally believed to as true coal, it is the initial stage in the coal-forming process, where the decomposing plant matter is begin to be compressed and heated.

Lignite: Peat is converted into lignite, or brown coal, the first type of true coal, by being compressed, heated more, and exposed to time. This coal has a low carbon content, but it is also highly volatile and must be constantly monitored because it has been known to self-ignite and burn readily if not dried properly. This coal is mostly used in steam power plants.

Sub-bituminous: The storage of energy in the form of preserved plant material is represented by coal, a solid fossil hydrocarbon. As a result of the preservation process, the plants have been reduced to organic matter, which consists of moisture, ash, volatile matter (gases and liquids released during heating), and fixed carbon. Energy is released when coal is burned, and both the fixed carbon and volatile matter contain energy.

Bituminous: The coal in the following stage has a high Btu value, is hard, and is a glossy, smooth black color. In addition, it contains bitumen, a sticky material utilized in the production of asphalt, which makes it challenging to dry the coal before burning. Because it doesn't produce a lot of slag or sticky particles when burned, a lot of this coal is used for the production of energy. It is also the kind of coal that is burned during the coking process to burn out all moisture and tar, only leaving carbon behind. Because it doesn't produce smoke, this coke is frequently used in stoves or furnaces when iron is being smelted.

Anthracite: The highest grade of coal is called anthracite, or hard coal, which has a metallic-like appearance, is extremely hard, and contains a lot of carbon. Even though it burns with a high level of energy for its mass, this form of coal is significantly uncommon and only makes up around one percent of all coal, making it exceedingly expensive to utilize. It does burn bright and smokeless, and in the places it is found, it is usually utilized for heating buildings and melting metal.

1.2 Moisture in Coal

Moisture in coal is typically caused by the presence of water molecules in the coal matrix. This water can come from a variety of sources including precipitation, surface water, or groundwater. It is important to measure the moisture content in coal as it can affect the heating value, combustibility, and handling characteristics of the coal. Following is a list of common moisture terms and its definition:

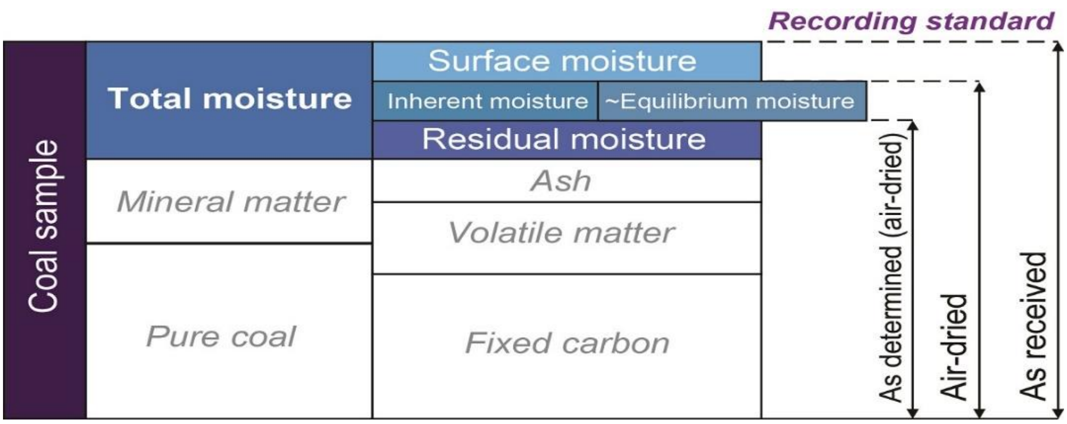

Figure 1: Coal samples contain several different types of moisture [9]

1.2.1 Need for high moisture coal drying

High moisture coal drying is necessary to reduce the moisture content of the coal in order to meet the requirements of the combustion process. Moisture in coal increases the cost of handling and storage and has a negative impact on the efficiency of combustion. The heat released by burning coal is used to generate electricity, so any moisture in the coal reduces the amount of heat available for power generation. Additionally, the presence of moisture can lead to slagging and fouling of the furnace walls, which can reduce the efficiency of the boiler. By drying the coal to a lower moisture content, the efficiency of the boiler can be greatly improved.

Each type of coal has distinct qualities, thus the drying process must be carried out differently. Drying coal makes it burn cleaner and more effectively. Vibrating Equipment has experience manufacturing coal dryers specifically for the coal industry, such as vibrating fluid bed dryers that fluidize and transfer sticky coals or systems that help prevent lignite explosions.

1.3 Fluidization

By passing gas through a bed of solid particles, a fluid-like state is created. This process is known as fluidization. This is achieved by passing the gas through the bed of particles at a velocity high enough to suspend the particles and create a particle layer. This layer of particles is constantly re-circulated, allowing the particles to move freely and interact with each other, allowing the particles to act like a fluid. This fluidization process allows for increased interaction between the gas and the particles, creating a more efficient exchange of mass and energy between them.

1.3.1 The basic theory behind fluidization of particle layers and the approach through which these layers are generated.

1) The material layer's state changes from a static state to a bubbling state when it is fluidized. The particle layer has the characteristics of a liquid. The ability of heat to transfer from the fluid to particles quickly grows as the increase in particle surface area in contact with the fluid.
2) Initially material particle layer is in the static state also known as a fixed bed at point O shown in the Figure 1.3. Now the fluidization phenomenon requires an increase in pressure and velocity to obtain a dynamic state, here in O to A region air passed to a fixed bed opposes the gravitational force of particles with a gradual increase of pressure drop with respect to an increase in velocity.
3) On further increasing the flow of hot air to a crucial state, the weight of the particle equivalent to the upward pulling force supplied by hot air. A complete fluidization state is achieved when the particles layer is fully suspended in the air stream as shown in regions A to B in Figure 1.2 also known as the bubbling phenomenon.
4) On increasing air velocity after point B leads to slugging within the material bed layer, in this region each and every particle is surrounded by the air stream due to which large turbulence is observed in heat and material transfer.
5) As the airflow reaches point C, lighter-density particle floats on top of the bed layer and the particle with high-density sink to the bottom of the material bed.

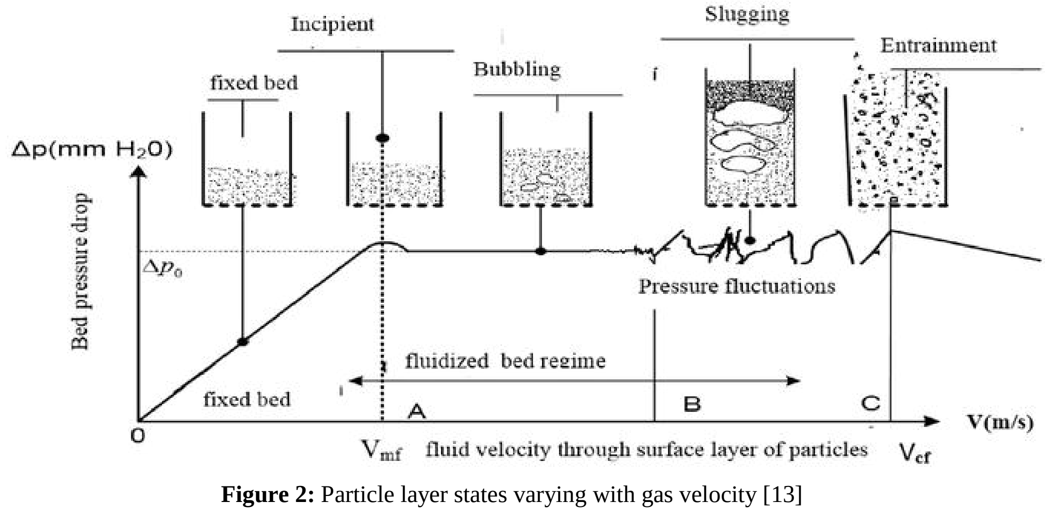

Figure 2: Particle layer states varying with gas velocity [13]

1.3.2 Conventional fluidized bed dryer

A conventional fluidized bed dryer is a type of industrial dryer that is used to dry a variety of materials, including powders and granules. The dryer uses hot air to fluidize the bed of material, suspending the material in the airflow and allowing it to dry. The fluidized bed dryer is often used in the drying of pharmaceutical powders and granules, as well as food products. It is also used to dry a variety of other materials, including plastics, chemicals, and even animal feed. The fluidized bed dryer is often more efficient than other types of dryers, such as tray dryers or drum dryers, as it allows for a more even drying of the material.

1.3.3 Vibration Assisted Fluidized Bed Dryer

A vibration assisted fluidized bed dryer is a type of drying equipment that uses vibration to fluidize and move the material being dried through the bed of the dryer. The vibration is typically generated by a motor or an air blower and helps to keep the material in constant contact with the hot air stream, which helps to speed up the drying process. The vibration also helps to prevent clumping or agglomeration of the material, which can result in uneven drying or poor product quality. This type of dryer is often used for drying powders, granules, pellets, and other materials that need to be uniformly dried.

2. Methodology

Cogeneration Power Plant (CPP) at Gayatrishakti Paper & Board Limited.

The Power Plant here is of 4MW and AFBC boiler with a capacity of 30TPH. The coal used in the boiler is High Calorific Value (CV) and Low Calorific Value (CV). But the majorly used is Low CV coal with a water content of 35- 45% (wet basis) imported from Indonesia. The approximate analysis of coal is as follows:

2.1 Approximate analysis to determine moisture content in coal

2.1.1 The method used at Gayatrishakti Paper And Board Limited is thermal drying method using oven

The moisture determined as mass lost from a sample under specific conditions following heating in a moisture oven is the moisture value provided for proximate analysis of oven temperature to 104 to 110° (ASTM method D3173-11, 2013, p. 494–497) as follows:

a) Crush and grind raw coal into small particles.
b) Then pass this crushed coal through a 2 mm screen, and collect the coal powder.
c) Weight 100g powdered coal and spread it on a dish.
d) Keep this dish in the oven for drying at 100±5°C till there is no change in weight of sample, approximately 45 min.
e) After drying take the sample out of the oven and keep it in an insulated place till room temperature is obtained.
f) Then again weigh the dry coal and obtain moisture content by following the formula:

$$\text{Moisture Content, M (\%)} = \frac{\text{Coal weight before drying – Coal weight after drying in oven}}{\text{Coal weight before drying}}$$

2.1.2 Gross Calorific Value (GCV) of Coal Using Bomb Calorimeter

Figure 3: Bomb Calorimeter

In our industry GCV of coal is calculated using Bomb Calorimeter. The procedure to find GCV using a Bomb calorimeter is as follows:

1. Grind the coal sample obtain from an oven known as Air-dried Basis (ADB) or direct obtain from raw coal known as Air-received basis (A.R.B) into a very fine mesh.
2. Take the coal powder < 1 gm. & make the tablet of it using its die & again take the weight of it, which should be in the range of (0.91 to 0.99) gm.
3. Now, take off a piece of thread & tie it to the thread, now keep the tablet in a small container such that tablet of coal is in contact with the thread to give fire.
4. Place setup in BOM & charge it with 30 Kg/cm2 of O2.
5. Now, take fresh water in a container & place BOM in it now connect the (+ve & -ve) cable to know the temperature of the coal tablet.
6. Now set the temperature reading to zero – reference button.
7. Display will show the increase in temperature as the tablet starts burning.
8. Now note the reading when the temperature stops increasing at the particular temperature & 2-time buzzer beep.
9. Hence calculate the GCV using the formula.

Water Equivalent Calculation (W.E):

$$W.E = \frac{CV\ (B.Acid) x\ Wt.of\ tablet + \{CVt + CVw\}}{T}$$

Where;

W.E = Water Equivalent (cal/°C)
CV (B. Acid) = Calorific Value of Benzoic Acid (KJ/kg)
Weight of tablet = {0.91- 0.99} gm
CVt = Calorific value of thread (21 kJ/kg)
CVw = Calorific valve of wire (9.32 kJ/kg
T = Temperature of reading (°C)

Cross Calorific Value (GCV): $$GCV = \frac{T\ x\ W - \{\ CVt = CVw\}}{M}$$

Where,

T = Temperature of reading (°C)
W.E = Water Equivalent (cal/°C)
CVt = Calorific value of thread (21 kJ/kg)
CVw = Calorific valve of wire (9.32 kJ/kg)
M = Mass of coal tablet (0.91 – 0.99) gm
GCV= Gross Calorific value of coal (kcal/gm)

Table 1: Approximate Analysis of Raw Coal (GCV=5400 kcal/kg)

Sr. No.	Moisture (%)	GCV of ADB	Ash (%)	GCV of ARB	Ash (%)
1	44.18	5634	7.52	3517	7.21
2	44.28	5634	7.14	3530	7.14
3	44.38	5433	7.29	3502	7.6
4	44.24	5415	9.47	3514	9.89
5	44.04	5458	8.33	3529	8.33
Average	**44.224**	**5514.8**	**7.95**	**3518.4**	**8.034**

Table 2: Approximate Analysis of Raw Coal (GCV=5700 kcal/kg)

Sr. No.	Moisture (%)	GCV of ADB	Ash (%)	GCV of ARB	Ash (%)
1	33.44	3958	11.34	5815	11.57
2	37.78	4098	8.33	5725	8.51
3	39.05	3966	8.42	5705	8.33
4	34.38	4311	8.51	5710	8.6
5	35.46	4261	8.5	5715	8.51
Average	**36.00875**	**4127.375**	**8.5425**	**5726.375**	**8.73375**

Table 3: Approximate Analysis of Raw Coal (GCV=6000 kcal/kg)

Sr. No.	Moisture (%)	GCV of ADB	Ash (%)	GCV of ARB	Ash (%)
1	32.52	4689	8.69	6013	8.24
2	31.94	4765	7.21	6025	8.16
3	32.36	4740	8.69	6027	8.33
4	32.6	4715	7.52	6029	8.51
5	32.48	4716	7.36	6003	7.44
Average	**32.38**	**4725**	**7.894**	**6019.4**	**8.136**

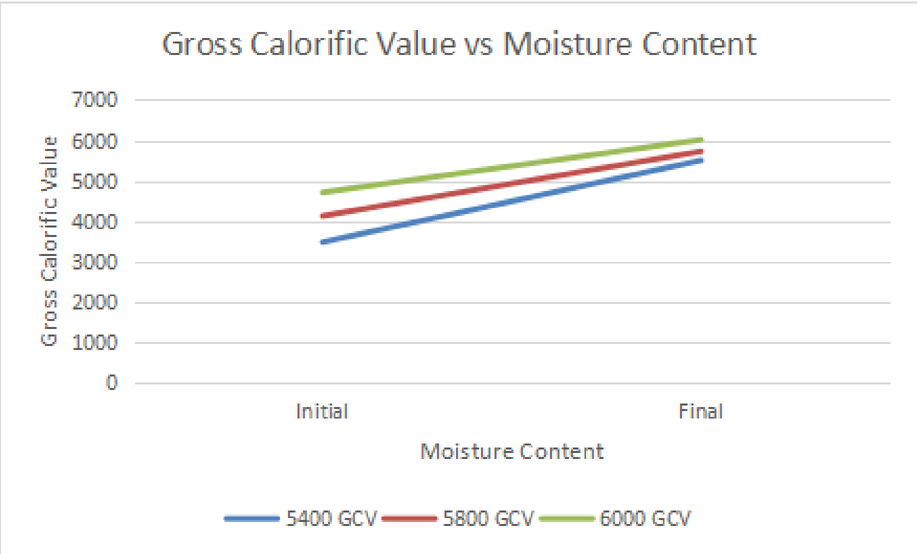

Figure 4: Comparison of Gross Calorific Value vs moisture content of available coal of three sample 5400, 5700 and 6000 kcal/kg.

2.2 Design and Development of Fluidized Bed Dryer

2.2.1 Wind Box Design

The wind box is chamber located below distributor plate. It is used for evenly distribution of air in vessel. When trying to expand out across the grid, including the corners, the air encounters additional resistance. Rearrangement resistance is the name given to this flow resistance. The side entry of air in the air box is shown in below Figure 2.3.

The air intake position below the grate may be selected as follows [22]:

$$Hb = 0.2Db + 0.5De \quad \text{if} \quad De > Db/100$$

$$Hb = 18\ De \text{ if } De \quad \text{if} \quad De < Db/100$$

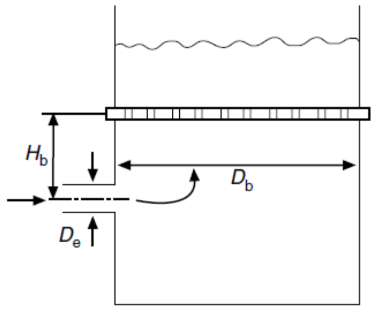

Figure 5: Wind box with side entry nozzle [22].

2.2.2 Air Distributor Plate

A perforated plate for a fluidized bed dryer is a plate with small holes or slots in it (orifice). This plate is placed in the bottom of a fluidized bed dryer to allow air to flow up through the bed and the material being dried. The perforations allow the air to flow freely and evenly throughout the bed, helping to ensure an even drying process. The size of the perforations can be adjusted to suit the needs of the specific drying process.

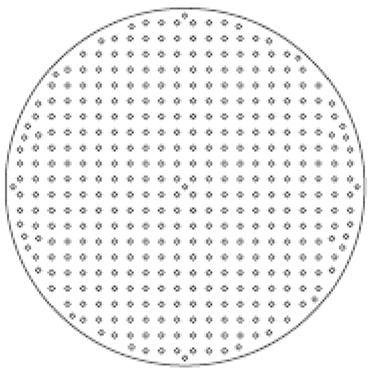

Figure 6: Perforated plate used in the experiment.

Table 4: Detail of multi-orifice distributor.

Distributor type	No. of orifice (N)	Orifice diameter do(mm)	Opening area of the orifice (%)	Orifice spacing/pitch in the square array P (mm)	Plate thickness t (mm)
Perforated plate	400	3	10	8.4	5

The equation for air distributor plate design [22].

The partial open cross section area of the orifices = n $\frac{\pi}{4}$ d_o^2

Here, n is number of holes depending on how the plate's orifices are arranged with pitch p:

$$n=\frac{2}{\sqrt{3}\ p^2} \quad \text{for triange pitch.}$$

$$n=\frac{1}{p^2} \quad \text{for square pitch.}$$

2.4 Experiment

2.4.1 Coal Properties

The coal used for the experimental study is both Low and High CV imported from Indonesia. The approximate analysis is listed in the table. These samples were crush and screen to the size fraction (1-5 mm). The raw coal used for experimental data and analysis were ARB, to determine residual water present in coal follow 2.1 discussed in detail.

2.4.2 Experimental Apparatus

The following are the details of the apparatus used to perform the experimental activity.

1. Rota-meter

A Rota meter is a type of flow meter used to measure the volumetric flow rate of a liquid or a gas.

It consists of a tapered tube, usually made of glass, with a float inside. The float rises and falls with changes in the discharge, and it can be read off a scale on the side of the tube. The range of Rota meter is 0 to 150 m3/hr.

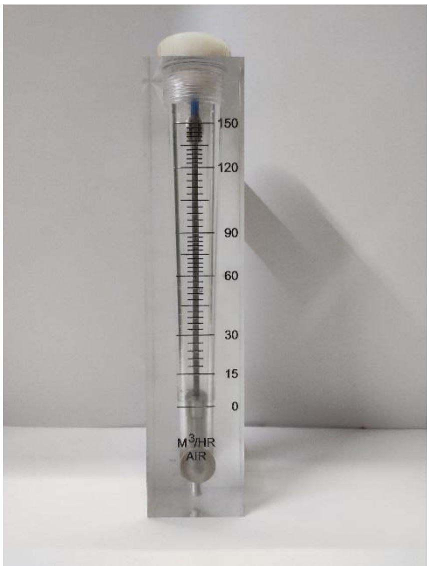

Figure 7: Rota meter.

2. Air finned heater

Finned air heaters are a form of heating element that is employed in various commercial and industrial applications. The heater is composed of a core of metal fins, which are heated by an electrical current that is passed through the fins.

As the fins heat up, they transfer their heat to the surrounding air, which is then used to heat the desired area. Finned air heaters are often used in applications such as air conditioning, heating systems, and industrial process heating. The capacity of air finned heater is 1000 W.

Figure 8 (a): Air-finned heating element.

Figure 8 (b): Air Heater.

3. Vibratory system

Vibrating tables are used to vibrate material in order to separate out particles, components, or substances.

The vibrating table usually consists of a metal platform that is mounted onto springs or other shock absorbers. The platform is then vibrated using a 12-volt DC electric motor. The vibration of the platform causes the material to separate out and settle into the desired configuration.

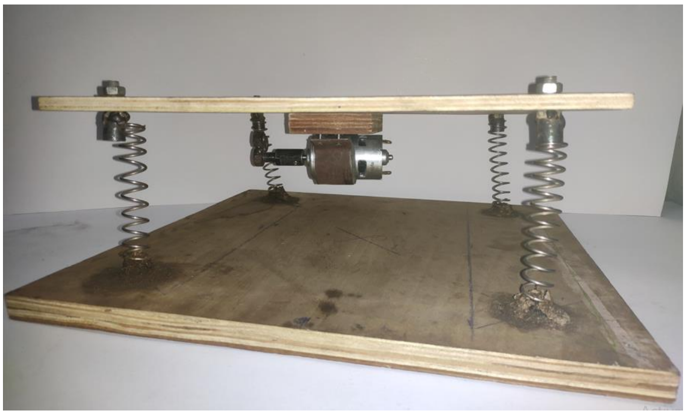

Figure 9: Vibrating System.

2.4.3 Experimental Procedure

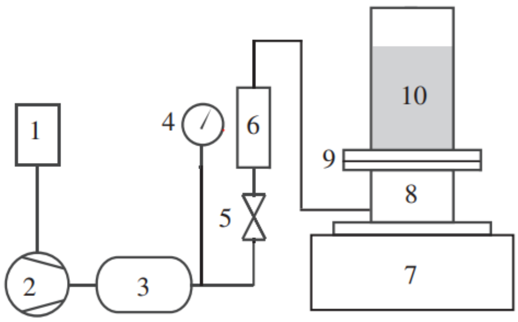

Figure 10: Schematic diagram conventional fluidized bed dryer [15].

1. Air filter; 2. Blower; 3. Tank; 4. A Pressure gauge; 5. Valve; 6. Heater; 7. Base; 8. Air chamber; 9. Air distributor; 10. Vessel.

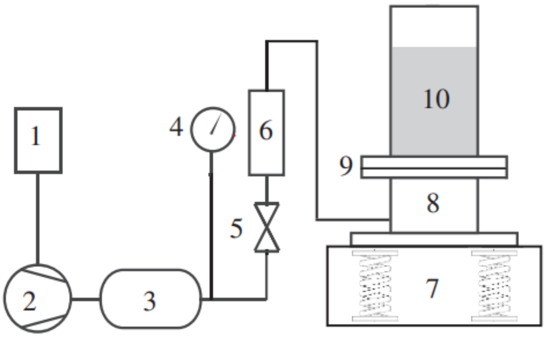

Figure 11: Schematic diagram conventional fluidized bed dryer (Modified) [15]

1. Air filter, 2. Blower, 3. Tank, 4. A Pressure gauge, 5. Valve; 6.Heater, 7. Vibrating Bed, 8. Air chamber, 9. Air distributor, 10. Vessel.

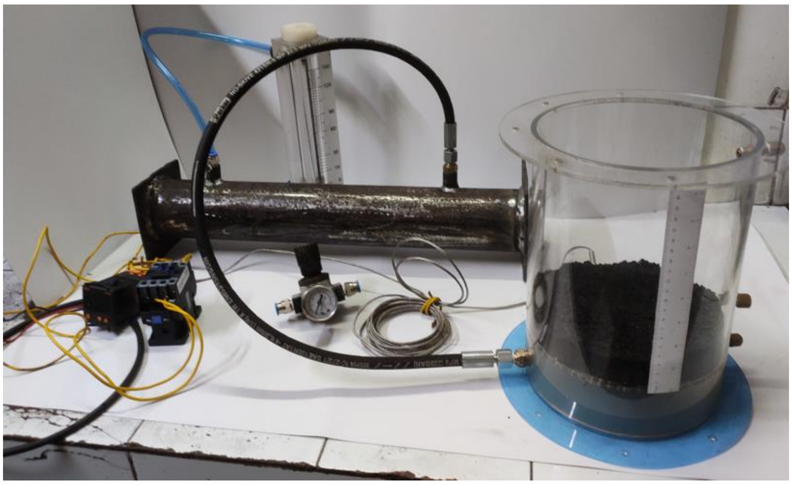

Figure 12 (a): Actual experimental setup for coal drying without vibration – front view

Figure 12 (b): Actual experimental setup for coal drying without vibration – top view

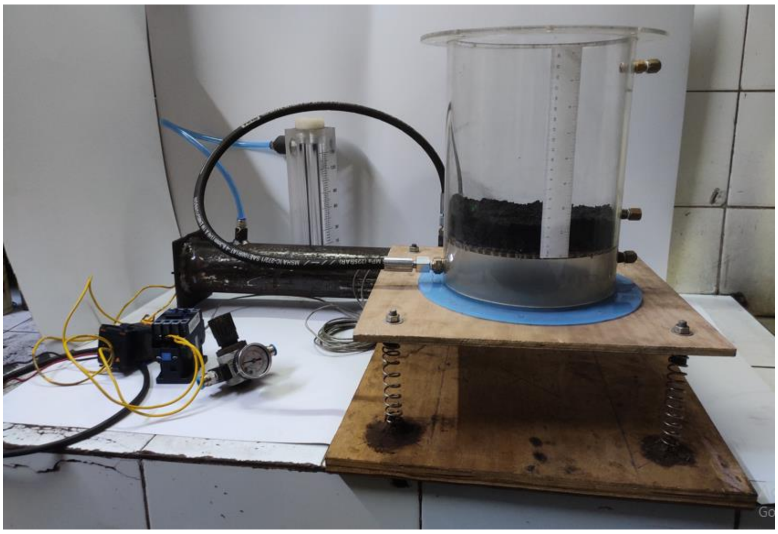

Figure 12 (c): Actual experimental setup for coal drying with vibration – front view

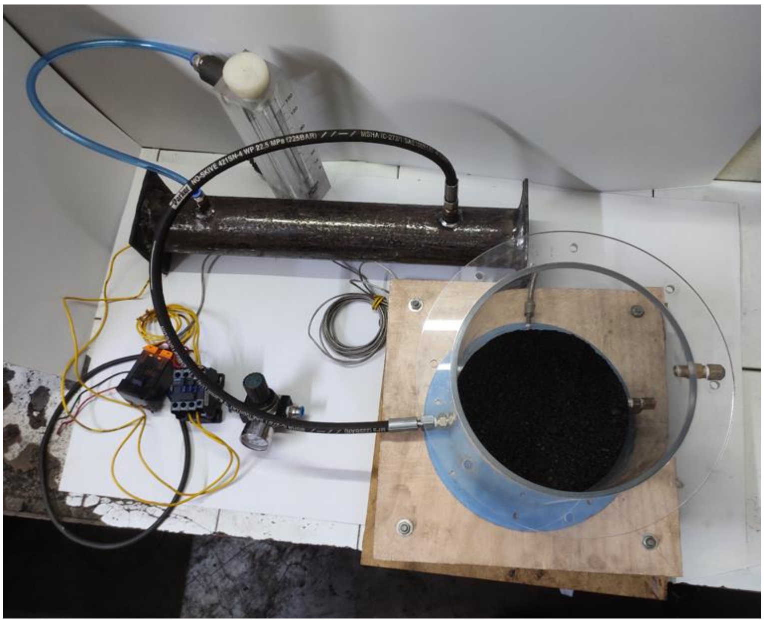

Figure 12 (d): Actual experimental setup for coal drying with vibration – top view

The image shown in the Figure 12 (a), (b), (c), (d) is the experimental setup used for performance in this study. The vessel with 200 mm diameter, a wall thickness of 4 mm, and a height of 280 mm made of acrylic material. The air generated in a compressor is regulated using a regulator and the flow rate is measured using a Rota meter. This air is preheated in an Air-finned heater before supplying to the wind box. The temperature of hot air is controlled by a temperature controller and sensor attached to the wind box.

The hot air from the wind box is used to dry wet coal particles resting on the distributor plate having an orifice diameter of 3 mm. The screen of mesh No. 40 is attached to the distributor plate, so then fine coal powder does not enter the wind box located at bottom of the distributor plate.

Following are the steps to perform the experiment activity:

- The raw coal obtained from the coal yard is crushed and passed to screen as per the required particle size to perform experiment operation.
- The dryer's empty cylinder received heated air that had been adjusted to the desired air flow and temperature.
- After it reached an equilibrium state, the moist solid sample was put into the dryer's empty cylinder.

- At regular intervals, a scoop of dried coal was taken from the dryer's top.
- The average weight of sample was considered as 15g, and their masses were recorded while they were in a desiccator.
- After taking a weight (15g), sample were sent to per-heated oven at100±5℃. (See 4.1.1)
- The moisture content of each sample at a specific time interval was determined using the weight difference.

Table 5: Operating condition for experiment.

Operational Parameter	Contents/Conditions
Bubbling gas	Air
Particle density	700 – 760 kg/m3
Particle size	1 - 5 mm
Temperature of gas	40-80 ℃
Bed height	20 - 40 mm
Minimum fluidization velocity (Umf)	0.14 – 0.43 m/s
Frequency	110 – 340 Hz

3. Results and Discussion

3.1 Results and discussion

3.1.1 Influence of Vibration Frequency

The fluidized bed (without vibration) and the vibration-fluidized bed were compared for moisture content and drying time is shown in Figure 3.1.

Initially, the moisture content for all operating conditions is the same, as the time duration increases and the frequency rate increases the moisture in coal evaporates faster, so we can say that increase in vibration frequency is advantageous for Low CV coal drying. While performing this experiment particle size: 2-3mm, temperature: 100℃, bed height: 40 mm, and v=0.29 m/s were kept constant.

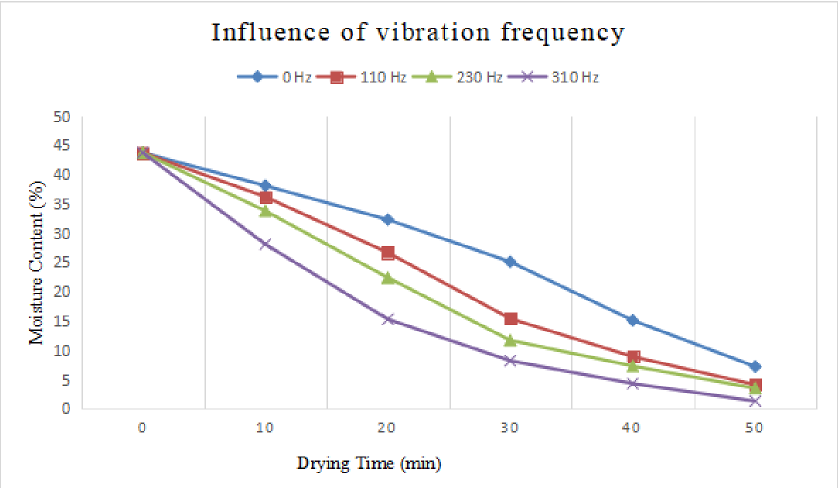

Figure 13: Influence of Vibration Frequency.

3.1.2 Influence of initial air temperature

The drying process is significantly influenced by the air temperature that enters Low CV coal in a vibration fluidized bed dryer. The drying process will proceed more quickly the higher the incoming air temperature. This is due to the fact that the heat energy from the incoming air will speed up drying by increasing the rate of evaporation.

Additionally, the quantity of moisture that can be extracted from the coal increases with temperature. It should be mentioned that coal can be harmed by too high temperatures, which will reduce its efficiency. Here the Particle size: 2-3mm, Bed Height: 40 mm, velocity=0.29 m/s, f = 230 Hz were kept constant for varying temperature 70°C to 110°C.

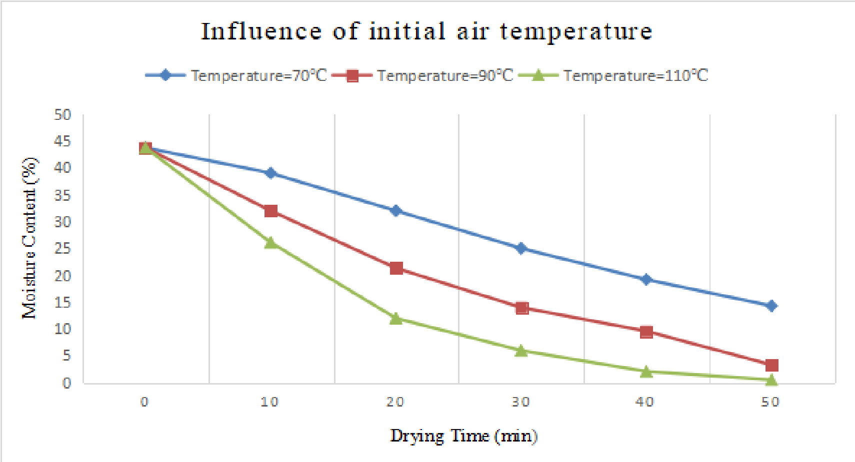

Figure 14: Drying characteristics for various inlet air temperature.

3.1.3 Influence of bed height

The variation of the moisture content with drying time was studied for three different bed heights 40, 60, and 80 mm. While performing the experiment for different bed heights the other parameter such as Particle size: 2-3mm, Temperature: 90°C, v=0.29 m/s, f = 230 Hz. With the increase in bed height, moisture content increases at the same drying time as shown in figure 3.3.

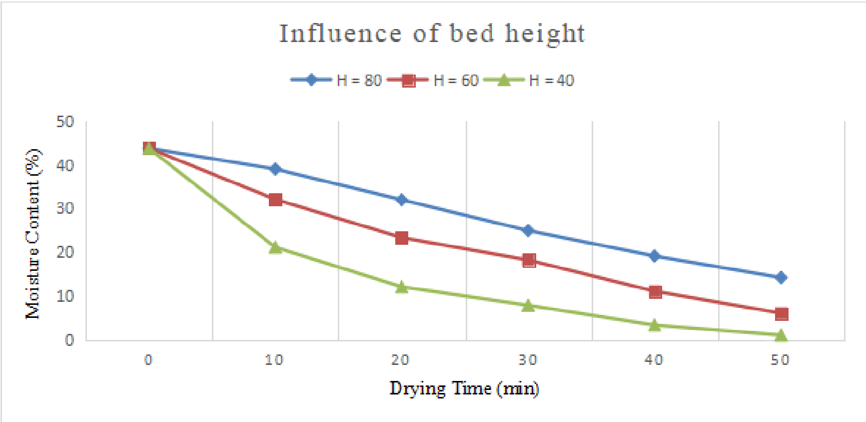

Figure 15: Drying characteristics for various bed height.

3.1.4 Effect of air velocity

The effect of air velocity on moisture content is shown in figure 3.4. These results implied that a considerable increase in air velocity reduces the moisture content from low CV coal particles because the increase in air velocity increases resulted in a rise in heat and mass transfer between hot air and coal particle. While performing the experiment for different bed heights other parameters such as Particle size: 2-3mm, Temperature: 60°C, f = 230 Hz, and bed height: 40 mm.

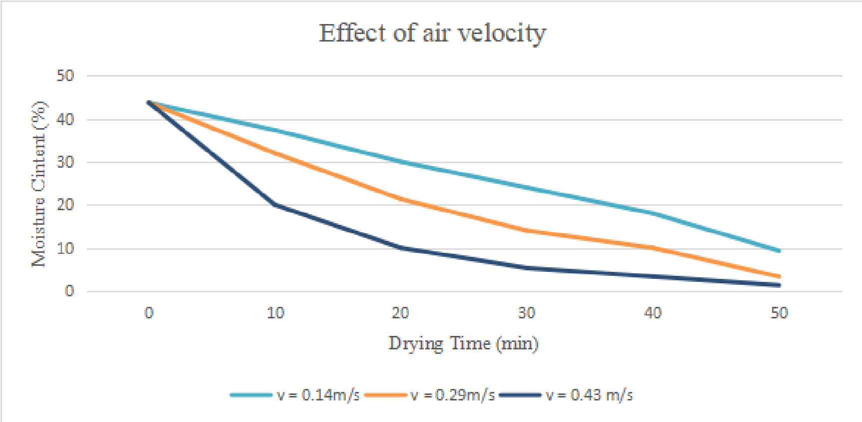

Figure 16: Drying characteristics for various air velocity.

3.1.5 Effect of particle size

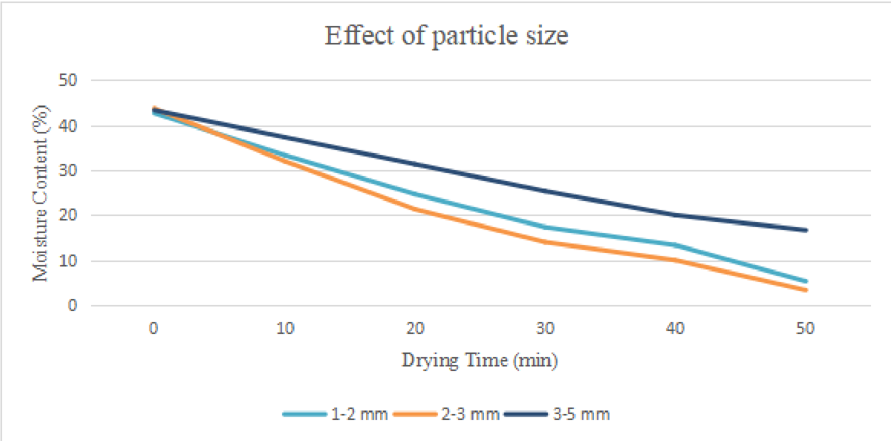

Figure 17: Drying characteristics for various particle size.

Comparing change in moisture content with different particle sizes (1-2, 2-3, 3-5 mm) at the same operating conditions which is temperature: 60℃, bed height: 40 mm and velocity=0.29 m/s, and f = 230 Hz. An increase in particle size results in an increase in drying time as shown in figure 3.5. As the large and widely sized low CV particle were difficult to fluidize in a conventional fluidized bed (without vibration), this can be eliminated by adding vibration to the fluidized bed dryer.

4. Conclusions

Following points were concluded based on experimental data and analysis:

1. Introducing vibration helped to reduce bubbles, and superficial air velocity resulting in a more homogeneous mixing and thus an improvement of heat and mass in a fluidized bed is achieved.
2. The moisture content with respect to time decreases with an increase in temperature, air velocity, and vibration frequency, and also increases with an increase in bed height and particle size.
3. With the increase in drying time, it was observed that the particle size breaks into small particles.
4. Uniform fluidizing was difficult for large particle sizes (3-5 mm) of coal in conventional fluidized bed dryers, which were easily fluidized by adding mechanical vibration.

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