RTB Working Paper

Scaling out energy-efficient pneumatic drying technology in Tanzania

Dr Marcelo Precoppe

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INTRODUCTION

Pneumatic dryers, also known as flash dryers, are commonly used to dry granular material in many industries. In this kind of dryer, wet solid is transported by a hot airstream, reducing its moisture content as it moves. The solid remains inside the dryer for only a few seconds and this allows heat-sensitive materials to be dried at relatively high temperatures.

State-of-the-art industrial pneumatic dryers are used to process cassava in many tropical countries. However, small-scale pneumatic dryers are not widely available. Pneumatic dryers are simple to construct, but they must be properly dimensioned for the dryer to operate efficiently. The main components of a pneumatic dryer are burner, heat exchanger, fan, feeder, drying duct and cyclone.

This document is separated into three sections, the first section describes the dryer, designed, and dimensioned for an output of 295 kilograms per hour of product, at a moisture content level of 12% on a wet basis (wb). The second section describes the computer simulation of the drying process using Discrete Element Method (DEM) coupled with Computational Fluid Dynamics (CFD). The third section describes the performance evaluation of the dryer built in Tanzania.

SECTION 1: PNEUMATIC DRYER DESIGN

PROCESSING CENTRE OPERATION

The pneumatic dryer was designed and dimensioned to operate in a processing centre that works 8 hours per day and receives 7,000 kg of fresh cassava daily. That is equivalent to 875 kilograms of cassava per hour. The roots will be hand-peeled and grated into a mash. The mesh will be mechanically dewatered with a press and the resulting press cake will be pulverized. The obtained cassava grits will be placed on elevated platforms and sun-dried until a moisture content of 20%wb is reached. After that, the pre-dried cassava grits will be introduced to the pneumatic dryer, which will reduce the moisture content further down to 12%wb. Finally, the dried cassava grits will be milled with a hammer mill. Figure 1 shows the main units of operation and the cassava reduction in mass and moisture content.

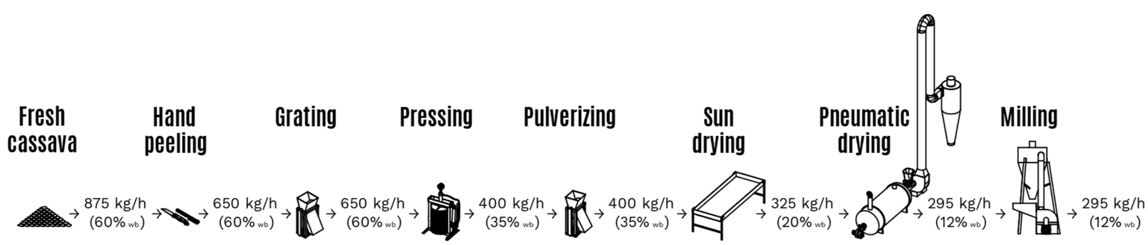


Figure 1. Overview of the cassava processing settings used to design and dimension the dryer.

DRYER COMPONENTS OVERVIEW

The dryer was designed to operate in Morogoro, Tanzania. Historical data of air temperature, relative humidity and pressure were used for the calculations. Figure 2 shows an overview of the dryer and Appendix 1 provides drawings of each component. All parts that come in direct contact with the cassava grits must be made of food-grade stainless steel. The drying duct should be thermally insulated. Air velocity inside the drying duct should be 8 m s^{-1} and temperature at the cyclone air outlet should be set to 60 °C.

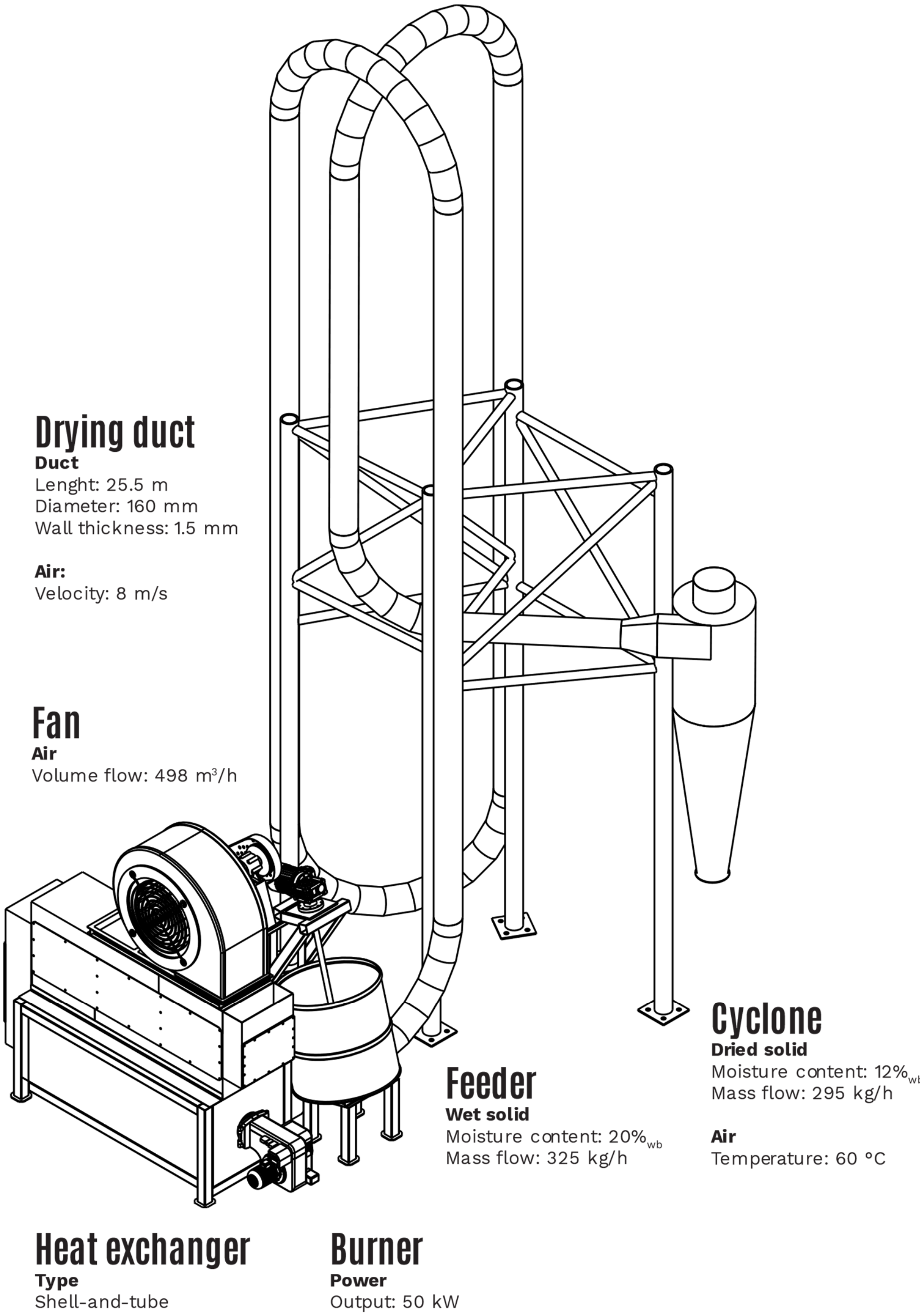


Figure 2. Overview of the designed and dimensioned dryer to operate at Morogoro, Tanzania.

BURNER

The burner's function is to fire the fuel and produce heat. For the designed dryer, the burner should have a power of 50.0 kW. A suitable burner is the Bairan, model B6 (35.5 kW to 71.0 kW). The burner must be thermostat-controlled, the temperature sensor should be placed at the cyclone air outlet (see Appendix 2 for further details) and the temperature should be set to 60 °C.

HEAT EXCHANGER

The heat exchanger has the function of transferring the heat that the burner has generated, to the drying air. The designed heat exchanger is of the shell-and-tube type. This type has a wide heat transfer surface and consequently higher efficiency. It contains a bundle of parallel tubes enclosed in a shell, as shown in Figure 3. A turbulator, placed inside each of the tubes (Figure 4), increases further heat and transfer surfaces.

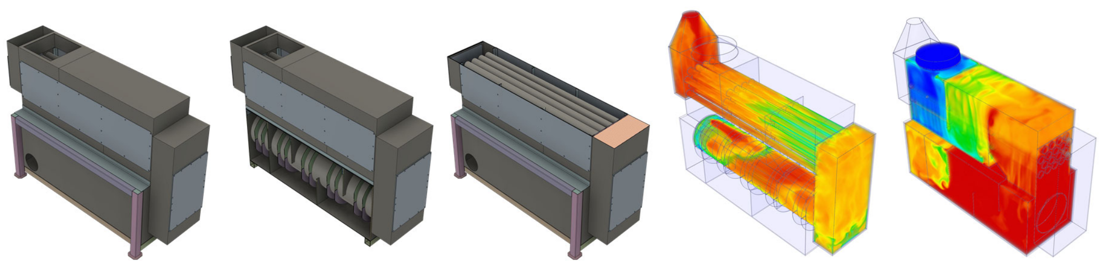


Figure 3. Shell-and-tube heat exchanger designed for the pneumatic dryer.

Figure 4. Turbulators are inserted into each of the heat exchanger's tubes to increase heat transfer.

FAN

The fan has the function to induce the air. The designed fan is a centrifugal blower with a squirrel-cage impeller (Figure 5). It should be powered by a 5.5 kW (7.5 HP) three-phase electric motor using a V-belt transmission. All belt drive components must be enclosed under a safety guard. The sizes of the pulleys of the power transmission need to be determined by trial and error until an air velocity, at the end of the drying duct, of 8 m s^{-1} is achieved (see Appendix 3 for a detailed explanation).

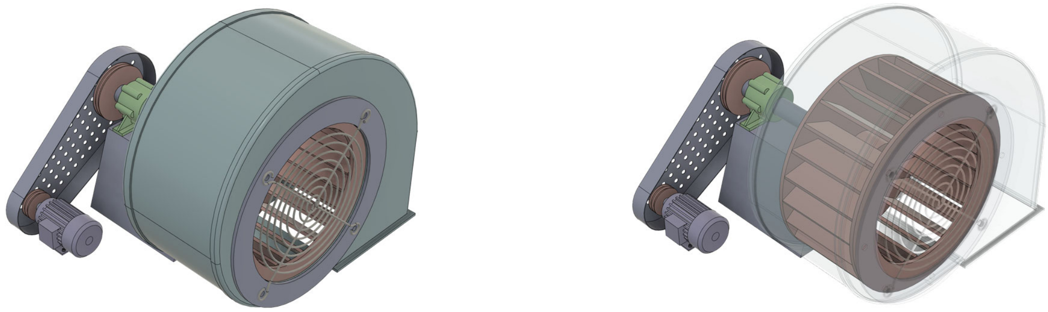


Figure 5. Centrifugal fan power by 5.5 kW three-phase electric motor using V-belt transmission.

FEEDING SYSTEM

The feeder has the function to introduce the material into the drying duct. For pneumatic dryers, the feeder must promote good dispersion of the solid in the airstream. Cassava grits are highly cohesive and can easily agglomerate into lumps. For this reason, the designed feeder has a hopper with a vertical wall, a slow-moving blade, powered by a 3.7 kW (5 HP) geared electric motor, and a venturi at the bottom (Figure 6). To avoid product agglomeration and formation of lumps, the blade of the feeder should move as slow as possible and therefore the slowest combination of motor and gearbox should be chosen. The speed that the blade moves has no relationship with the feeding rate. What determines the feeding rate is the size of the orifice opening, at the bottom of the hopper. The exact diameter of this orifice needs to be determined by trial and error using a weighing scale until the feeding rate of 325 kg h^{-1} is achieved, see Appendix 4 for further details.

Figure 1. Feeding system designed to avoid material agglomeration and formation of lumps.

DRYING DUCT

The drying duct is where the solid is dried. The drying duct must be long enough to provide the required residence time for the material to reach the target moisture content. Also, the drying duct must be thermally insulated to minimise heat losses. The drying duct should be built with 1.5 mm stainless steel sheets, rolled into ducts of 160 mm diameter. For the designed dryer, the total length of the drying duct is 25.5 m. To assure easy installation under a factory roof, without needing to make modifications, the drying duct was split into 3.5 vertical sections (Figure 7).

Figure 7. Drying duct, 25.5 m long, split into 3.5 vertical sections to assure easy installation.

CYCLONE

The cyclone has the function to separate the dried solid from the airstream. The dried cassava grits leave the cyclone from its bottom and the air exits from its top. The cyclone was designed using the Stairmand high-efficiency standard (Figure 8).

Figure 8. Stairmand high-efficiency cyclone to separate the dried product from the air stream.

SECTION 2: DRYER SIMULATION

OVERVIEW

A pneumatic dryer involves the flow of hot air and particle simultaneously. Therefore, to design, scale up, or optimize such a dryer, a deep understanding of its thermo-hydrodynamics is required, including the dynamic interaction between air, particles, and boundaries. Computer simulation can be a useful tool to understand it, but to simulate this granular-fluid system, Computational Fluid Dynamics (CFD) must be coupled with Discrete Element Method (DEM). CFD is the process of modelling mathematically the fluid flow by solving conservation equations for mass, momentum, and energy. CFD allows to simulate and predict fluid motion. Discrete Element Method (DEM) is a numerical technique used to simulate the motion of particles by solving Newton's second law of motion for each particle. DEM allows to simulate and predict the behaviour of granular material. Coupling CFD with DEM allows not only to simulate the interaction between the particle and the air but as well particle-particle interaction. Further, in a two-way CFD-DEM simulation, particle movements calculations considered the interaction with other particles as well the interaction with the airflow, while the airflow calculations also considered the presence of the particles.

COMPUTATIONAL FLUID DYNAMICS SETTINGS

The software Ansys Fluent was used to simulate the airflow inside the dryer. At the dryer air inlet, an air temperature of 249 °C and humidity of 0.016 kg kg^{-1} (0.06% relative humidity) was assigned. The SST k-omega viscous model was used and for the free convection coefficient, a value of 15 W m^{-2} K^{-1} was entered. Figure 9 shows the boundary conditions used for the CFD simulation.

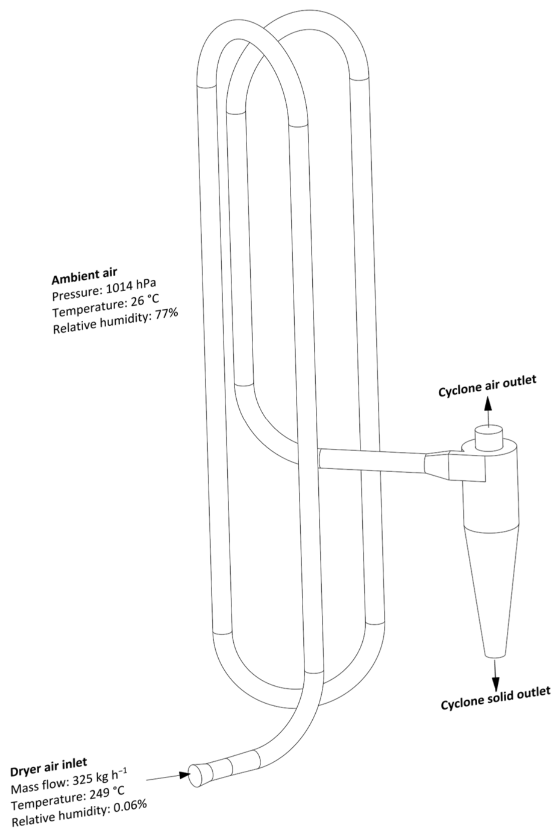


Figure 9. Boundary conditions that were used for the CFD simulation.

DISCRETE ELEMENT METHOD SETTINGS

The software ESSS Rocky was used for the DEM simulations. For normal contact forces, the Hysteretic Linear Spring Model was used. For the tangential contact forces, the Linear Spring Coulomb Limit model was used. To simulate the stickiness of the material the Linear Adhesive Force model was used and for rolling resistance the Linear Spring Rolling Limit model was used.

The cassava material was simulated with a bulk density of 682 kg m^{-3}, Young's modulus of 5 MPa, thermal conductivity of 0.57 W m^{-1} K^{-1}, specific heat of 2.2 kJ kg^{-1} K^{-1} and a Poisson's ratio of 0.25. Spherical particles with a diameter of 0.5 mm were used. They were inserted into the dryer at the feeder point at a rate of 325 kg h^{-1}, with a moisture content of 0.25 kg kg^{-1} on a dry basis, equivalent to 20%wb. Particles were inserted with a temperature of 36 °C.

SIMULATION RESULTS

Particle velocity is usually a difficult and complex measurement and most of the time only air velocity is measured, however, CFD coupled with DEM provides an estimate of particle velocity along the drying duct (Figure 10a) as well as the velocity of the air (Figure 10b). At the drying duct particle velocity was on average 6.9 m s^{-1}, ranging from 3.61 m s^{-1} to 11.3 m s^{-1} and with an average residence time of 6.4 seconds. At the cyclone particle velocity was on average 3.7 m s^{-1}, ranging from 3.2 m s^{-1} to 7.3 m s^{-1} and with an average residence time of 1.3 seconds. Figure 11 shows a plot of the particle velocity along the drying duct.

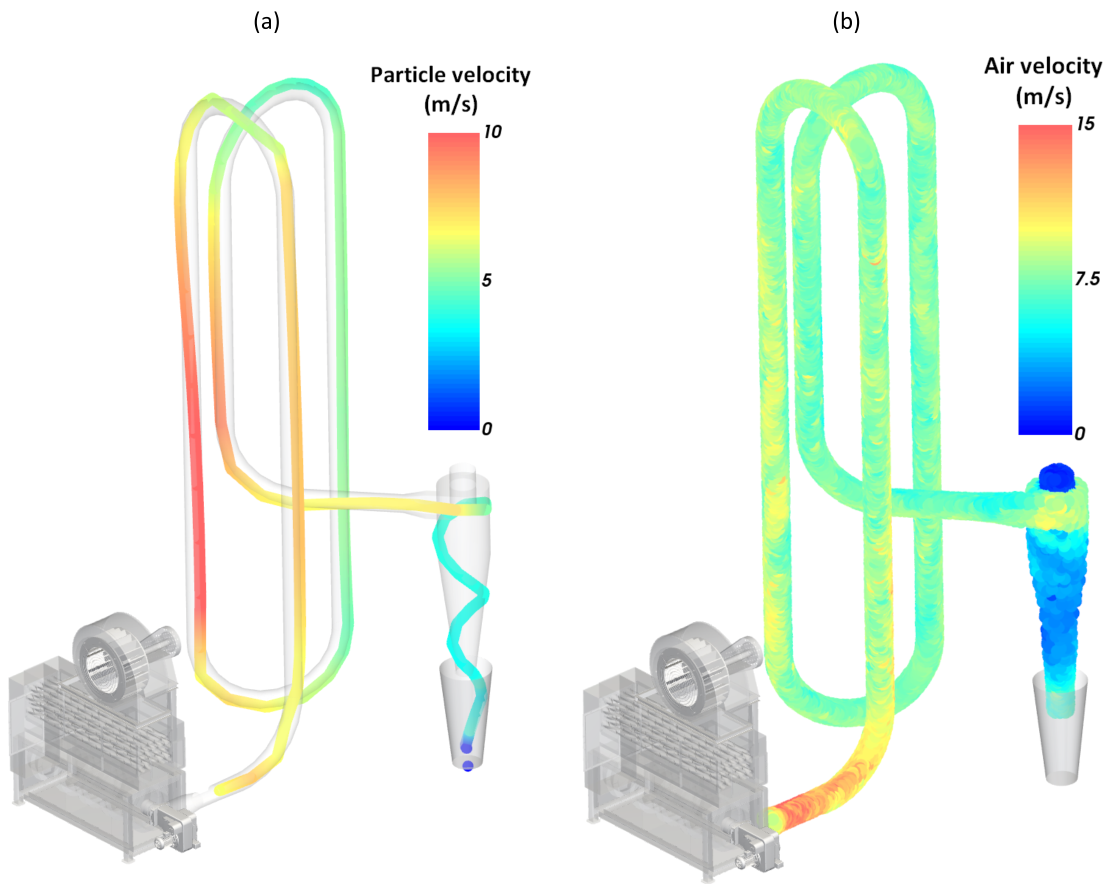


Figure 10. The velocity of (a) the particles and (b) the velocity of the air during drying.

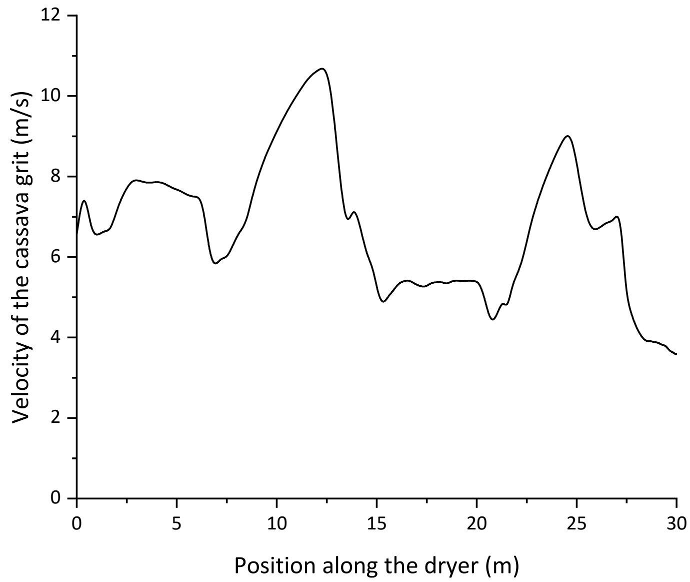


Figure 11. Particle velocity along the drying duct.

During drying operation, the temperature of the product before and after drying can be easily measured, but product temperature during drying is rarely done. Figure 12a shows the particle temperature during drying, inside the drying duct and Figure 12b show the air temperature. Additionally, Figure 13 shows a plot of the particle temperature along the drying duct. The maximum particle temperature was 58 °C and they left the dryer with a temperature of 50 °C.

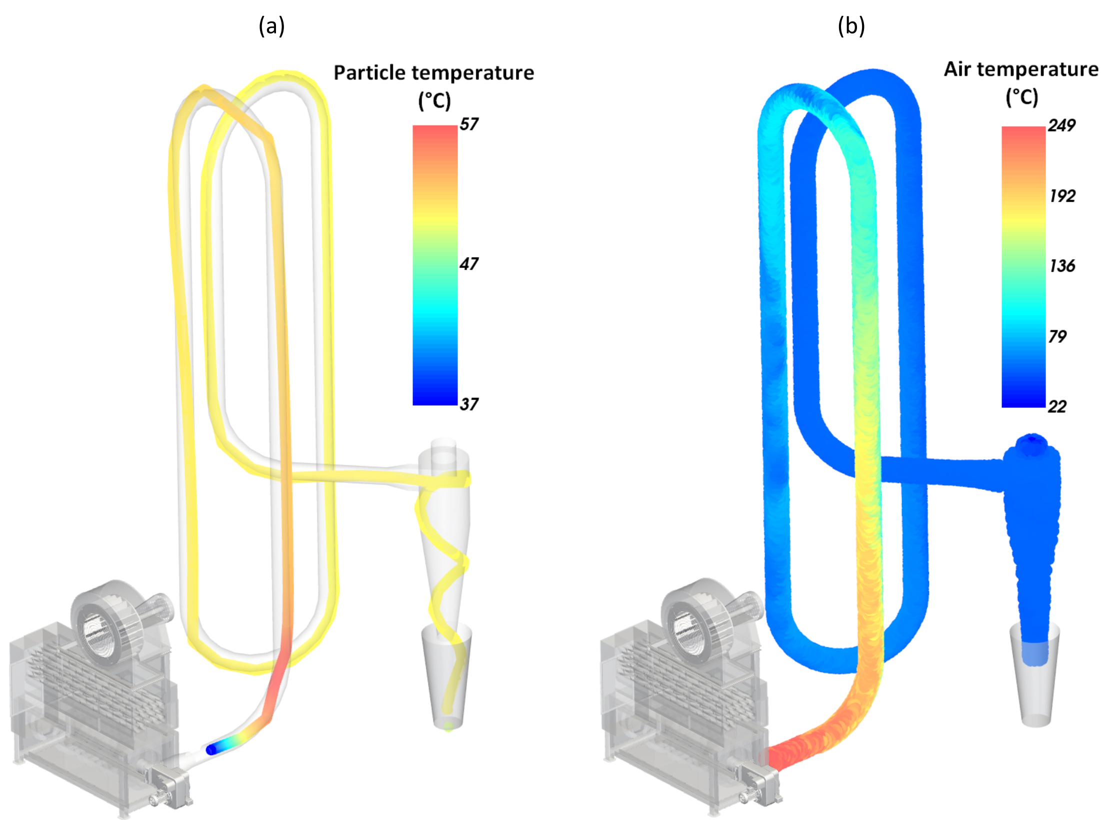


Figure 12. The temperature of (a) the particles and (b) the temperature of the air during drying.

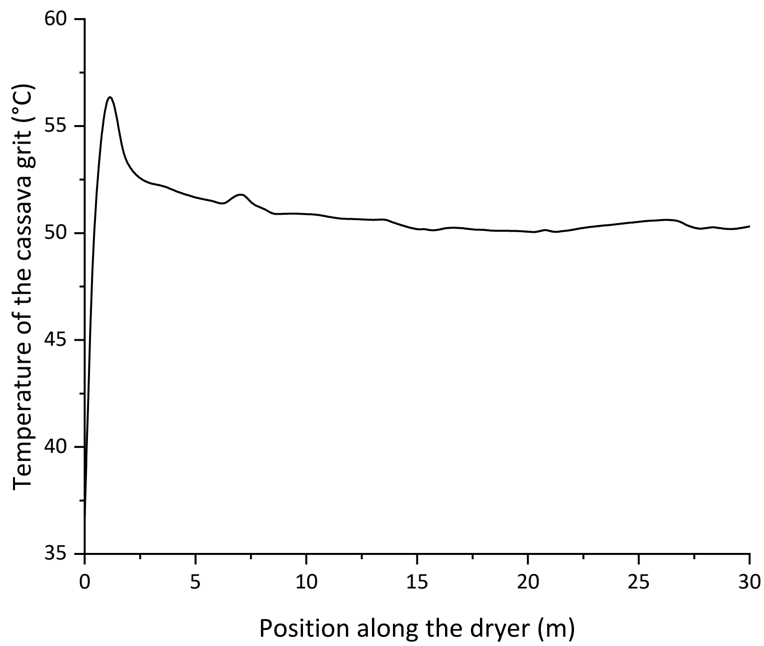


Figure 13. Particle temperature along the drying duct.

Figure 14a shows the reduction of the particle moisture content as it travels along the drying duct, and Figure 14b shows the increase in the air's mole fraction of water vapour. Product left the dryer with a moisture content of 0.14 kg kg^{-1} (12.3%wb) and air left the dryer with a humidity of 0.08 kg kg^{-1} (84% relative humidity). Figure 15 shows a plot of the particle's moisture content along the drying duct.

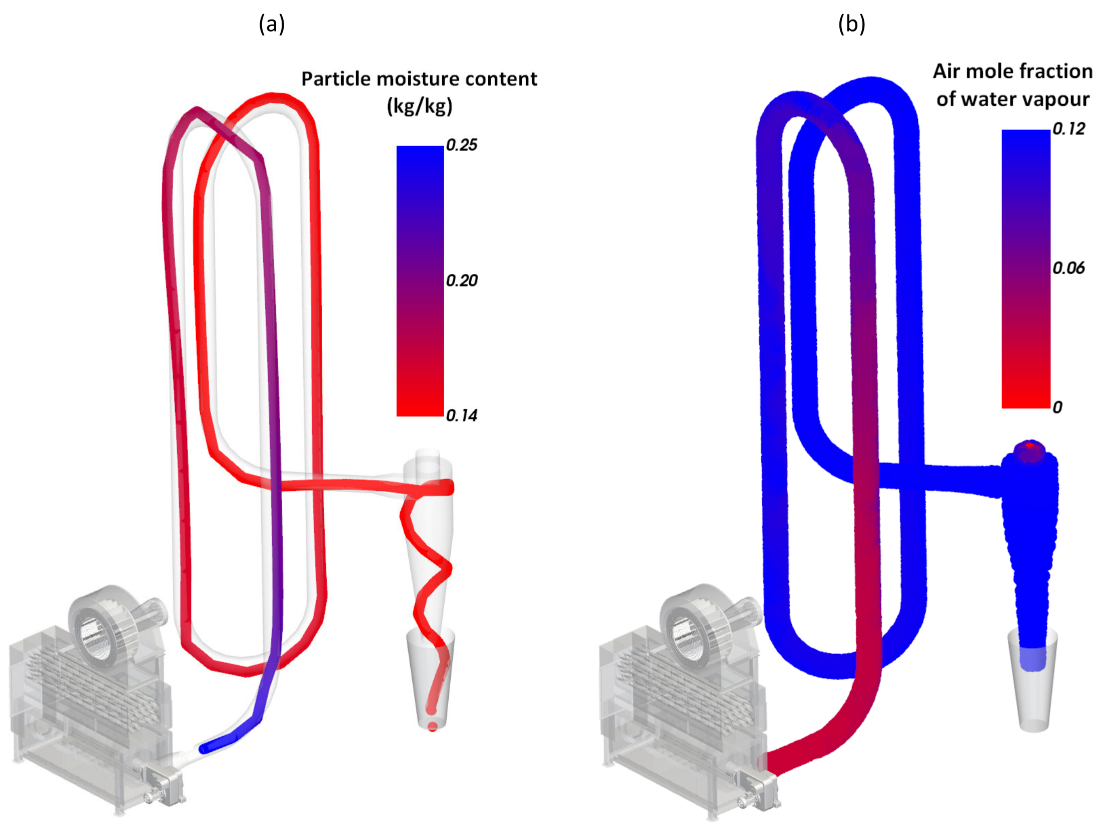


Figure 14. Water amount (a) reduction in the particle and (b) increment in the air during drying.

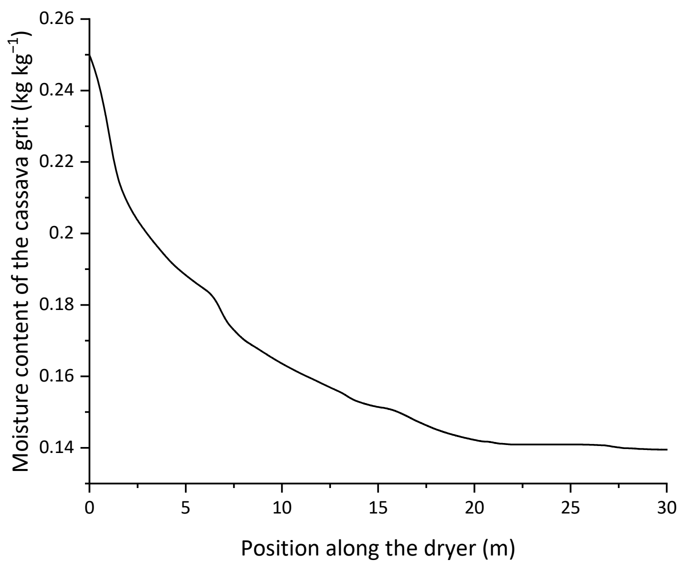


Figure 15. Particle moisture content along the drying duct.

Drag forces shown in Figure 16 provides an understanding of the interactions between particle and air. In addition, adhesive forces along the drying duct shown in Figure 17, provides an understanding of the particles collisions and agglomeration during drying.

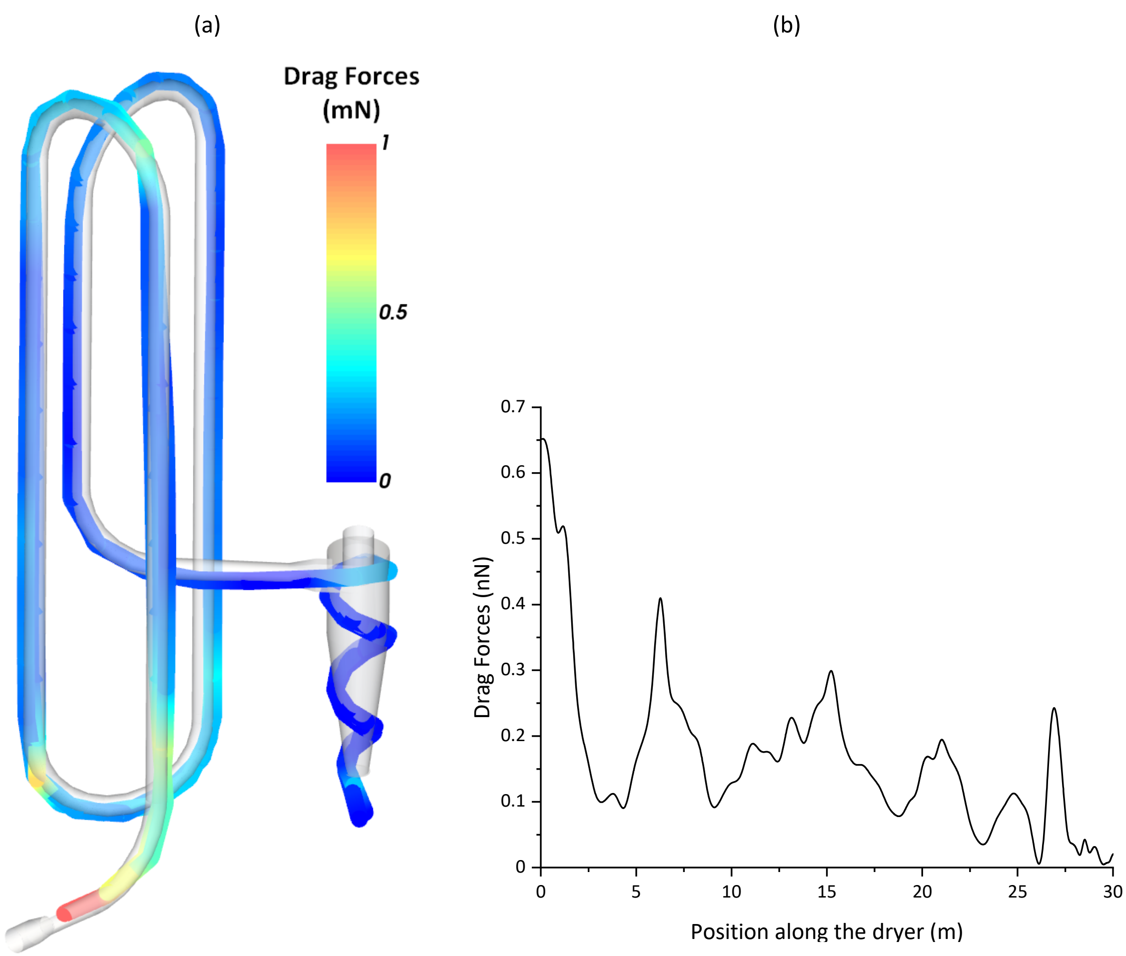


Figure 16. Drag forces along the drying duct.

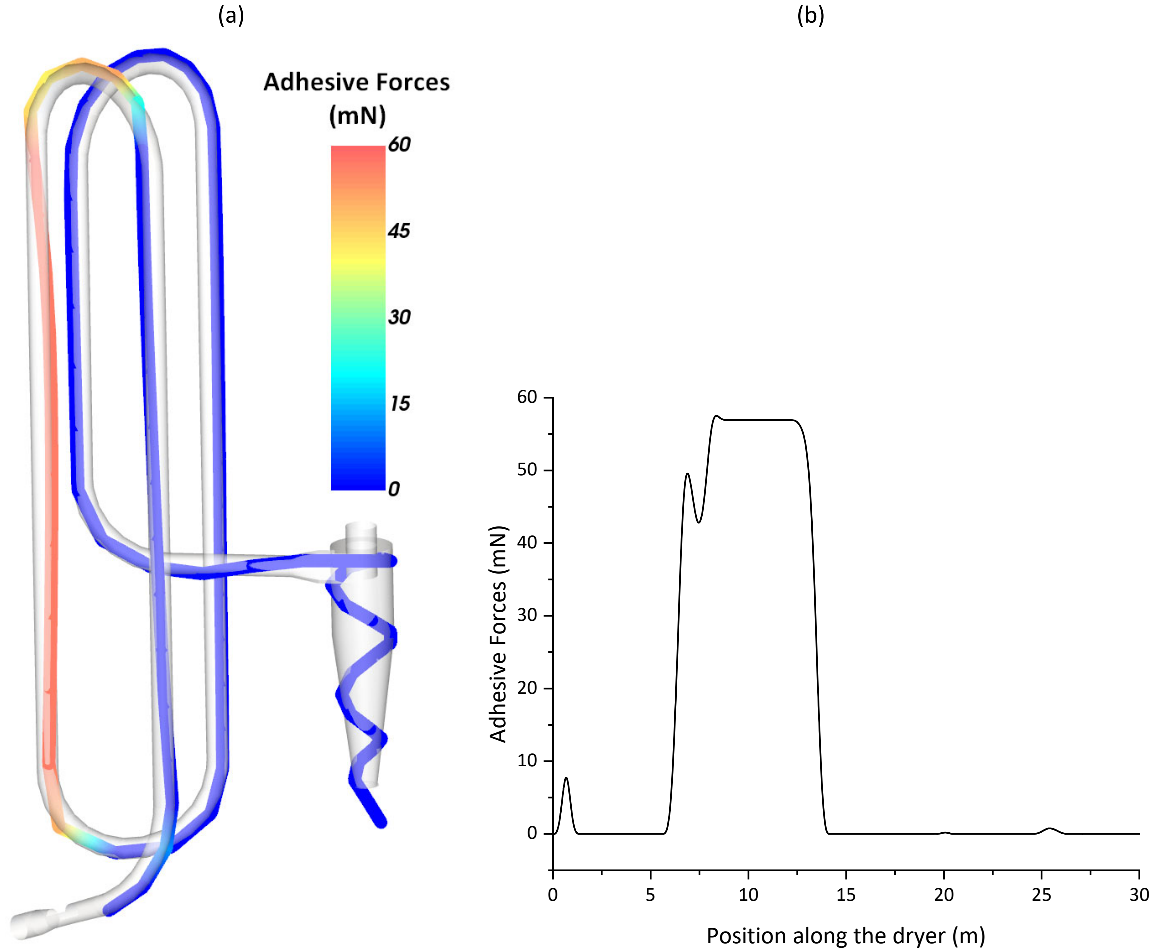


Figure 17. Particle adhesive forces along the drying duct.

SECTION 3: DRYER PERFORMANCE EVALUATION

The data collection procedure is described in Appendix 5. The values of temperature and relative humidity of the ambient air was used to calculate its enthalpy (h_{amb}), density, and the humidity of the air at the dryer inlet. The values of air velocity measured at the fan intake, and the area of its cross-section, plus the density of the air, were used to calculate the air mass flow rate ($\dot{m}_{air}$). With the measured value temperature at the dryer inlet and the calculated humidity at this location, the enthalpy of the air at the dryer inlet (h_1) was obtained. Heat input rate to the dryer ($\dot{Q}_{in}$) was calculated from the air mass flow rate, the enthalpy of the ambient air and the enthalpy of the air at the inlet (Equation 1):

$$\dot{Q}_{in} = \dot{m}_{air}\left(h_1 - h_{amb}\right) \quad (1)$$

Based on the values of moisture content of the cassava grits before (X_{ws}) and after drying (X_{ds}), plus the solid mass flow rate on a dry basis ($\dot{m}_{dm}$), the water evaporation rate ($\dot{m}_w$) was calculated (Equation 2):

$$\dot{m}_w = \dot{m}_{dm}\left(X_{ws} - X_{ds}\right) \quad (2)$$

To determine the amount of energy needed to evaporate one kilogram of water, specific energy consumption (q_s) was calculated dividing the heat input rate to the dryer by the water evaporation rate (Equation 3):

$$q_s = \frac{\dot{Q}_{in}}{\dot{m}_w}, \tag{3}$$

The heat rate used for moisture evaporation ($\dot{Q}_w$) was obtained by multiplying the water evaporation rate to its latent heat of vaporization (λ). Finally, energy efficiency was calculated dividing the heat rate used for moisture evaporation by the heat input rate to the dryer (Equation 4):

$$\eta = \frac{\dot{Q}_w}{\dot{Q}_{in}}, \tag{4}$$

During measurements ambient temperature was 35.8 °C, ambient relative humidity was 35% and atmospheric pressure was 1014 hPa. The volume of air passing through the dryer had a rate of 777.5 m^3 h^{-1} and the average temperature at the dryer inlet was on average 260 °C. The dryer was fed with cassava grits with a moisture content of 22%wb (0.28 kg kg^{-1}) at a rate of 325 kg h^{-1} and produced 280 kg h^{-1} of dried cassava grits with moisture content of 12% (0.14 kg kg^{-1}). Table 1 shows the calculated energy performance indices; however, it is expected that higher efficiency could be achieved if the dryer was operated closer to its design point.

Table 1. Energy performance indices of the pneumatic dryer used for cassava processing.

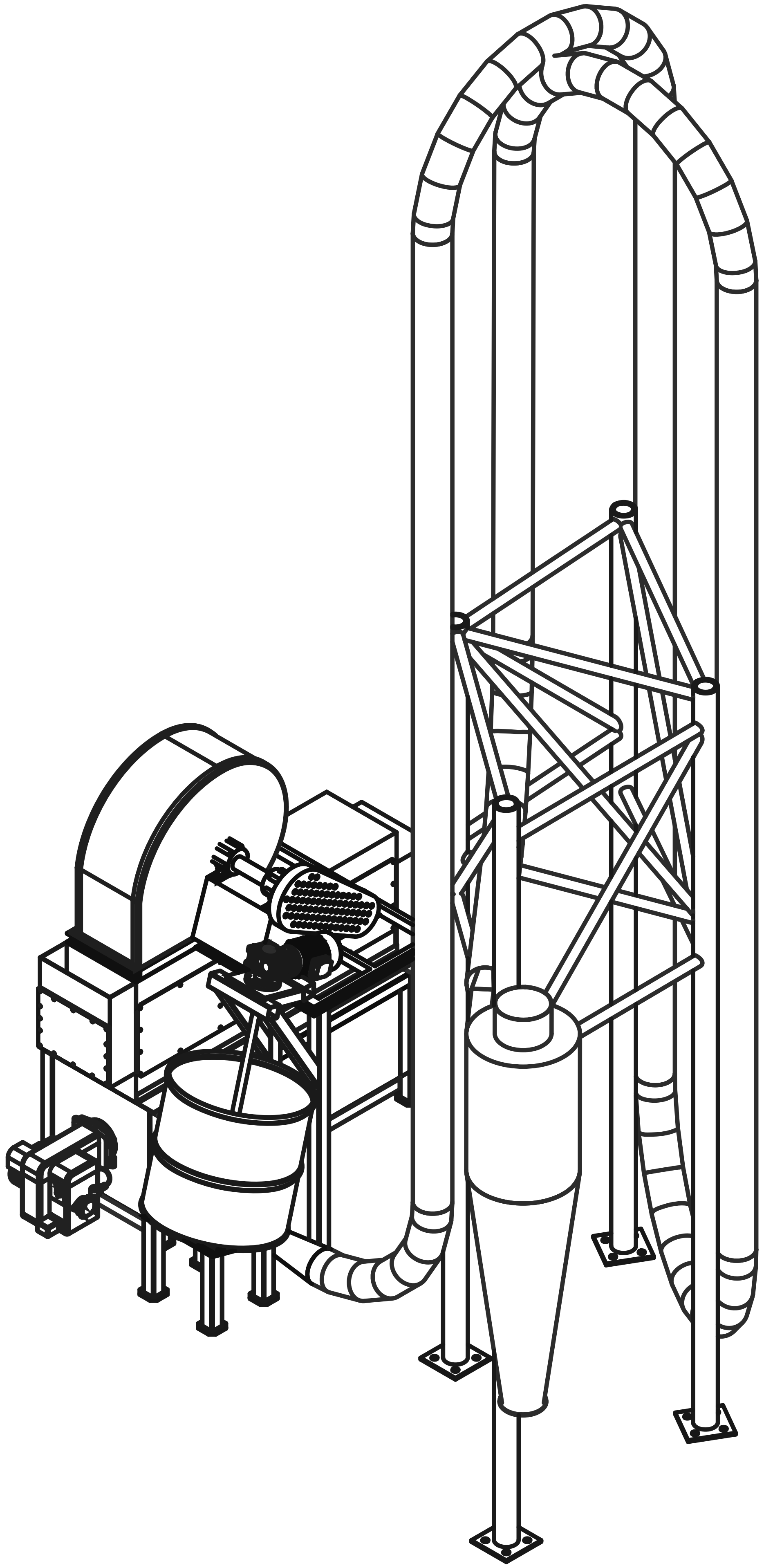
Heat input rate to the dryer	56.0 kW
Water evaporation rate	36.9 kg h^{-1}
Specific energy consumption	5.4 MJ kg^{-1}
Energy efficiency	45.5%

CONCLUSIONS

Pneumatic dryers are simple and equipment, with few moving parts and easy to manufacture. It is the most efficient equipment to dry cassava grits, but for its high efficiency to be achieved, the dryer needs to be properly dimensioned. To achieve this, computer simulation, particularly, Computational Fluid Dynamics coupled with the Discrete Element Method can be used, providing additional insights into the complex interaction between particles and the air, plus the interaction between particle and particle.

Appendix 1

Drawings of the pneumatic dryer and its components



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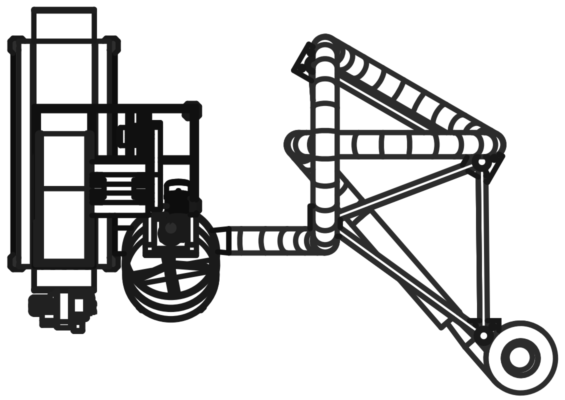

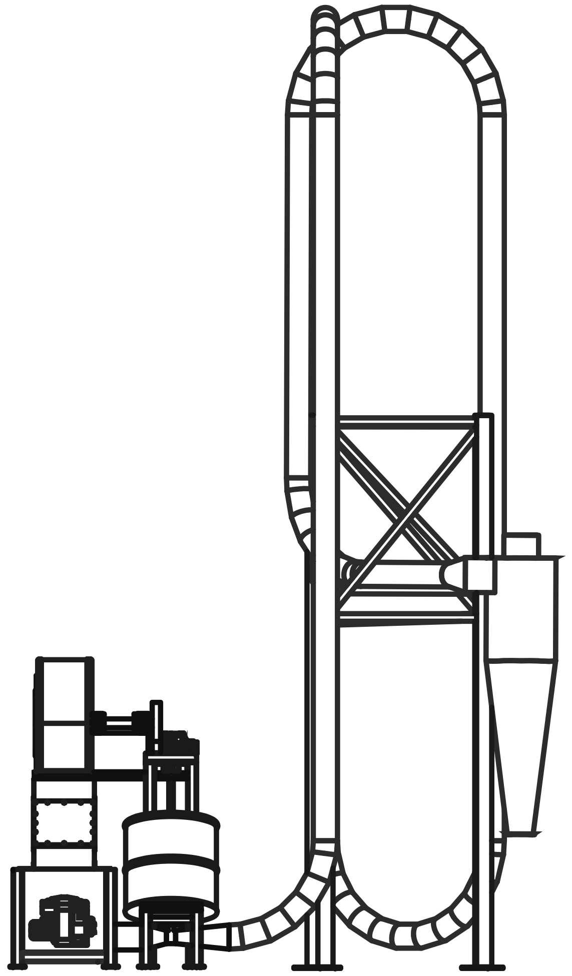

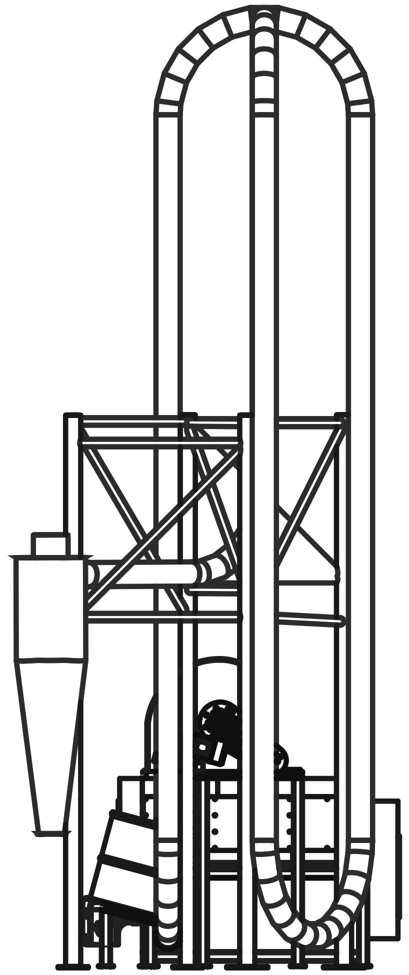

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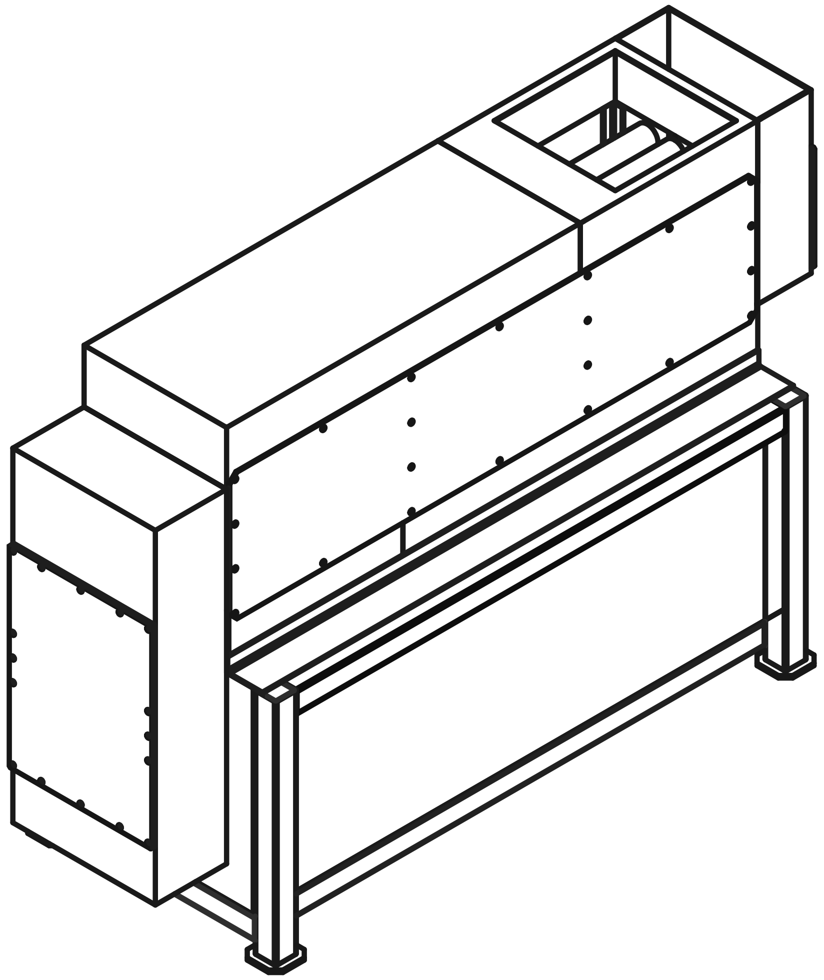

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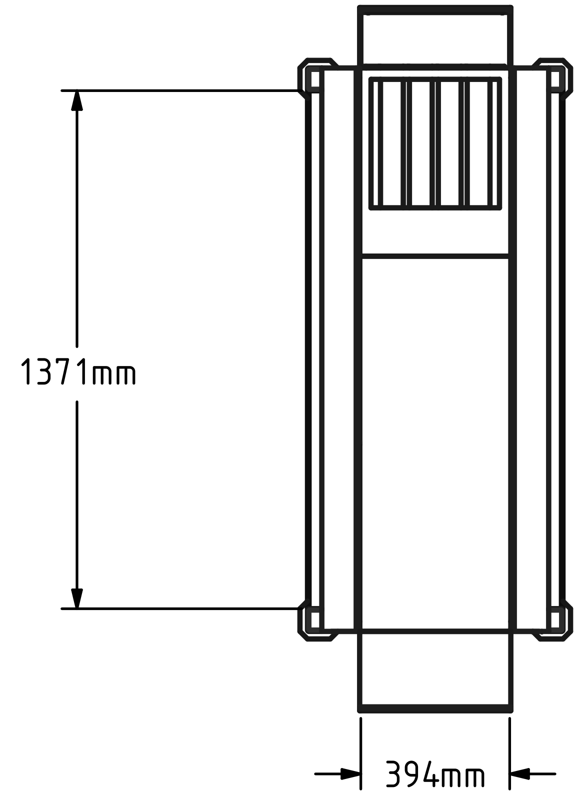

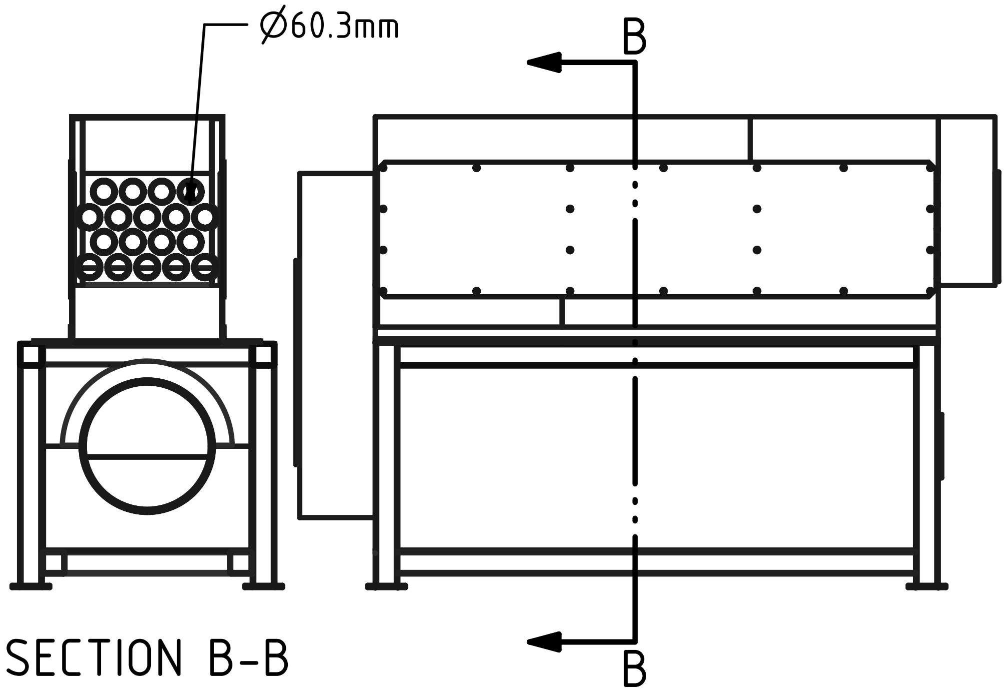

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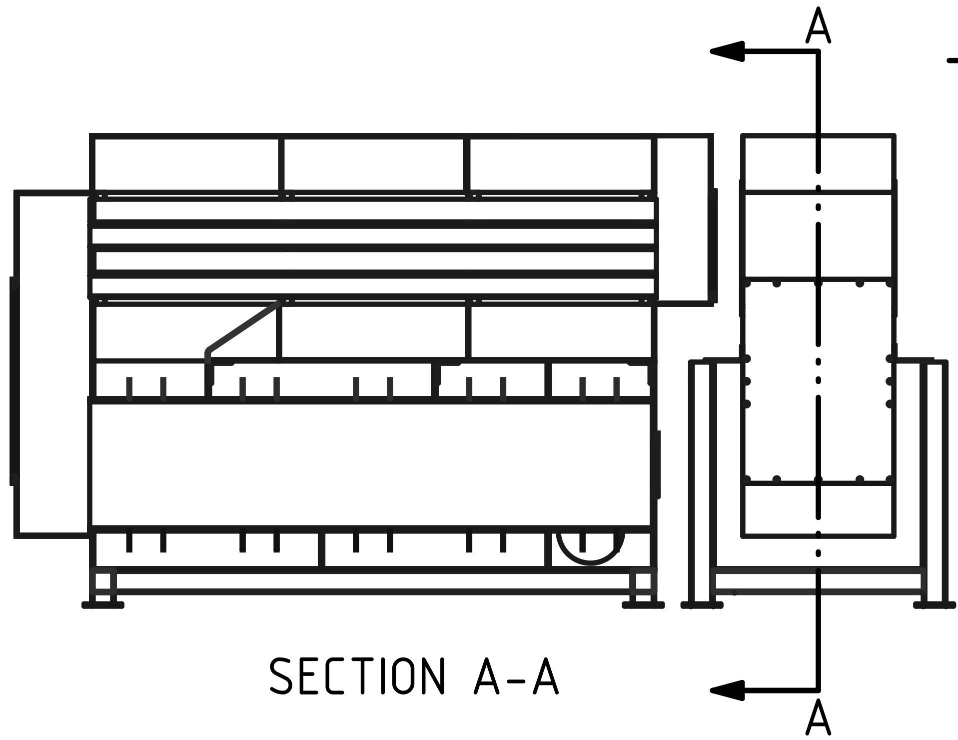

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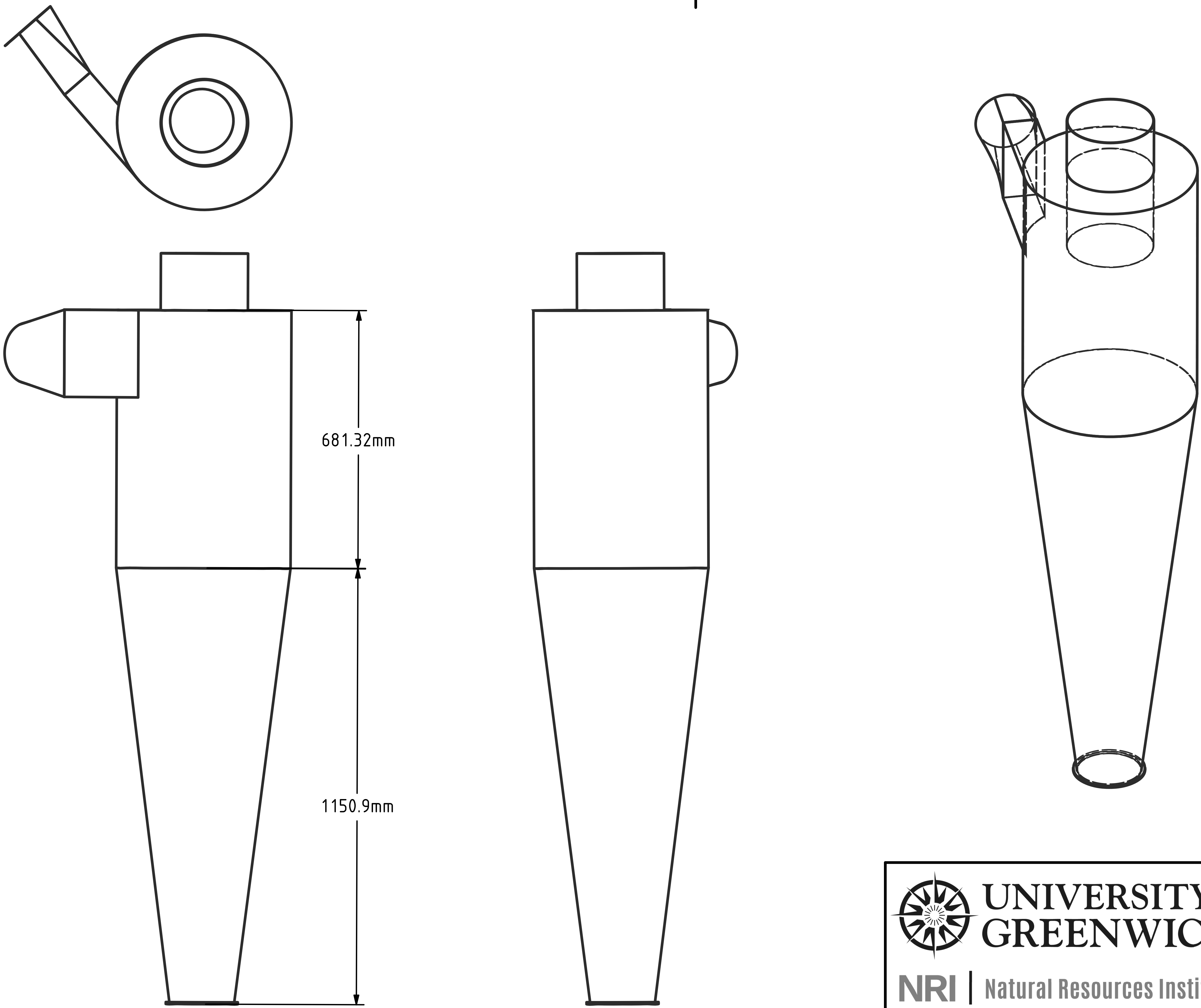

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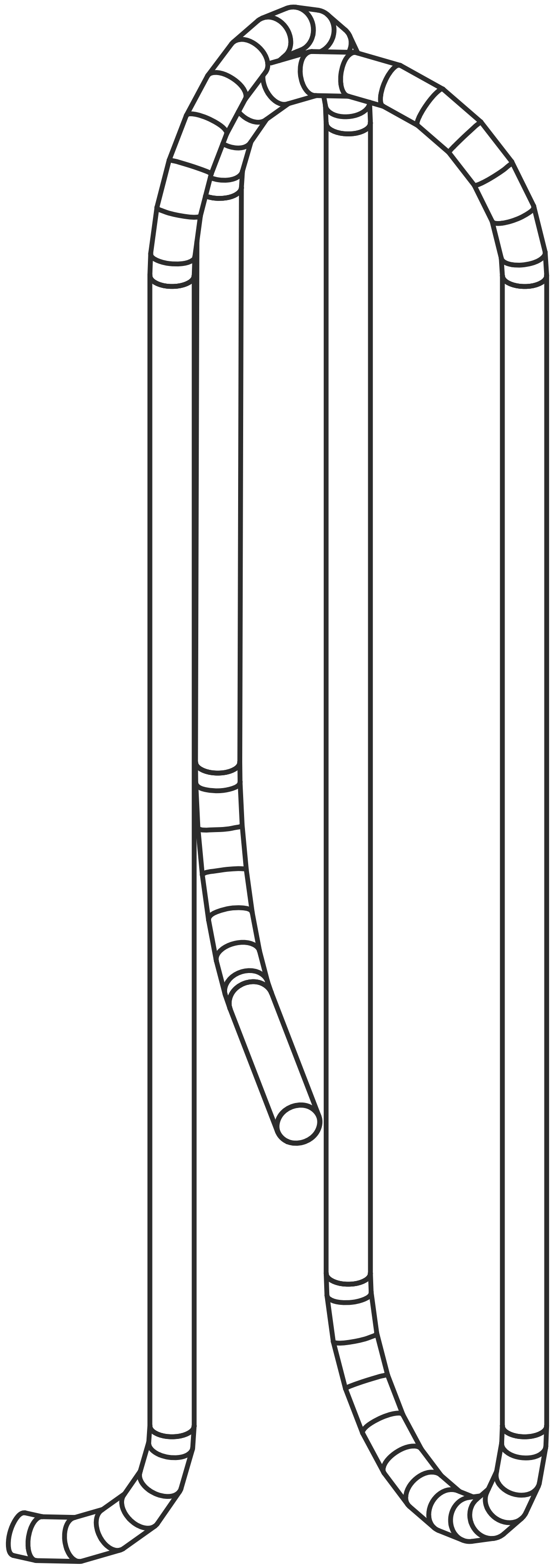

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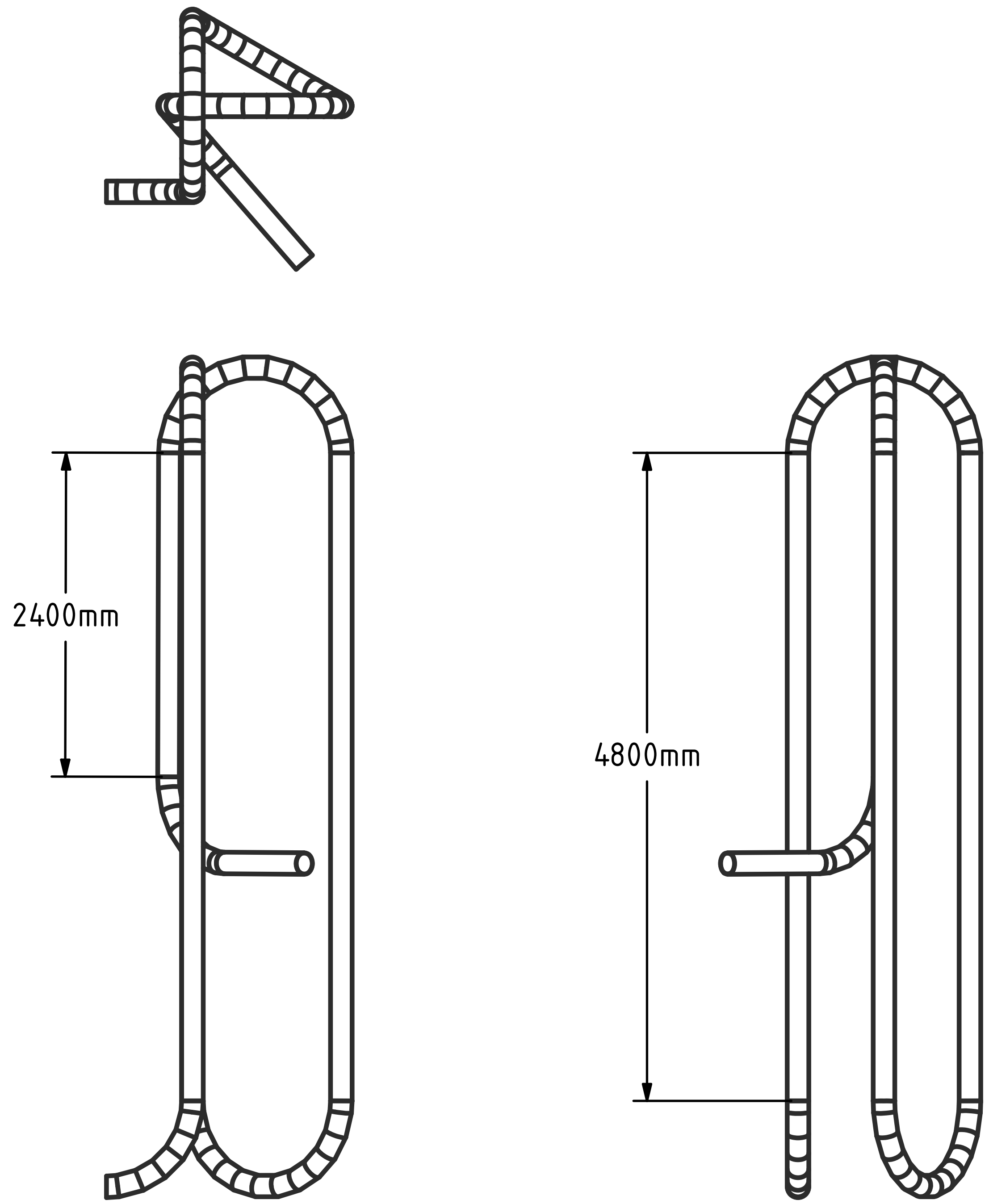

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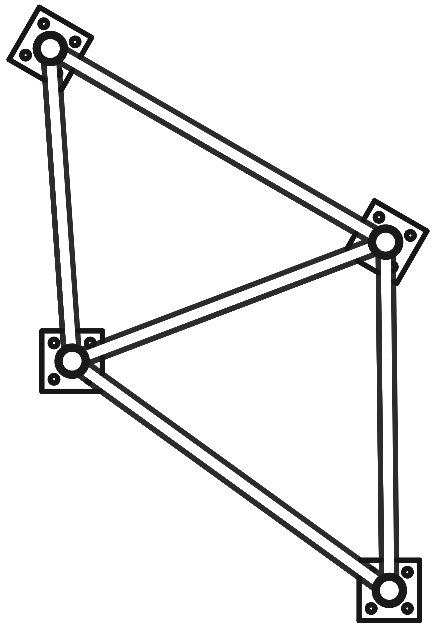

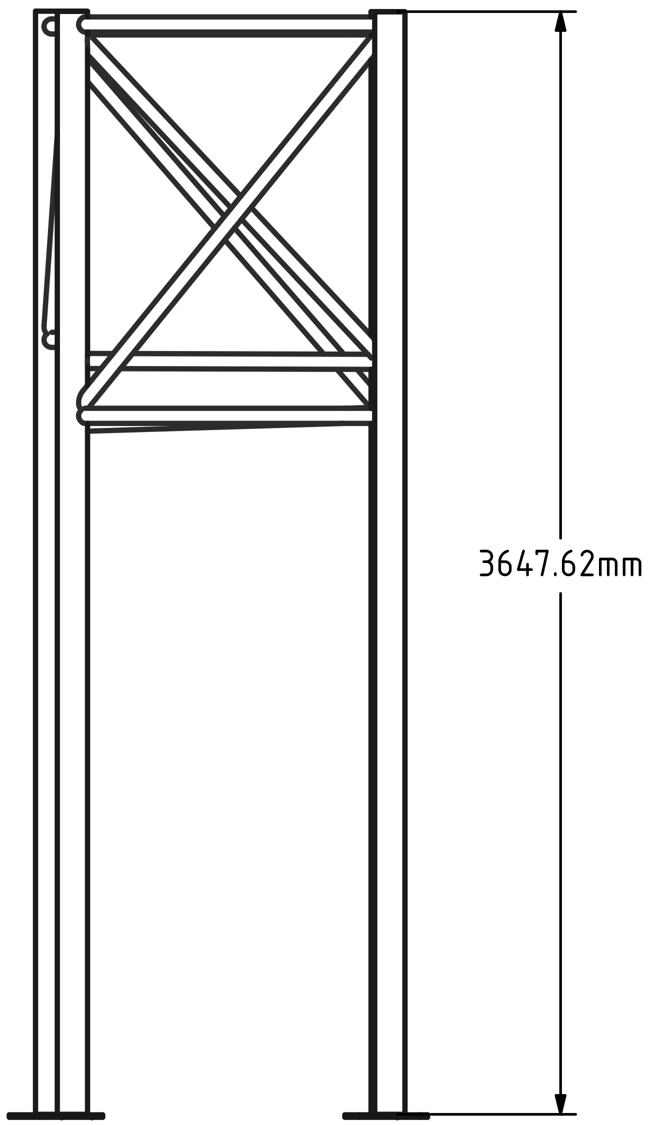

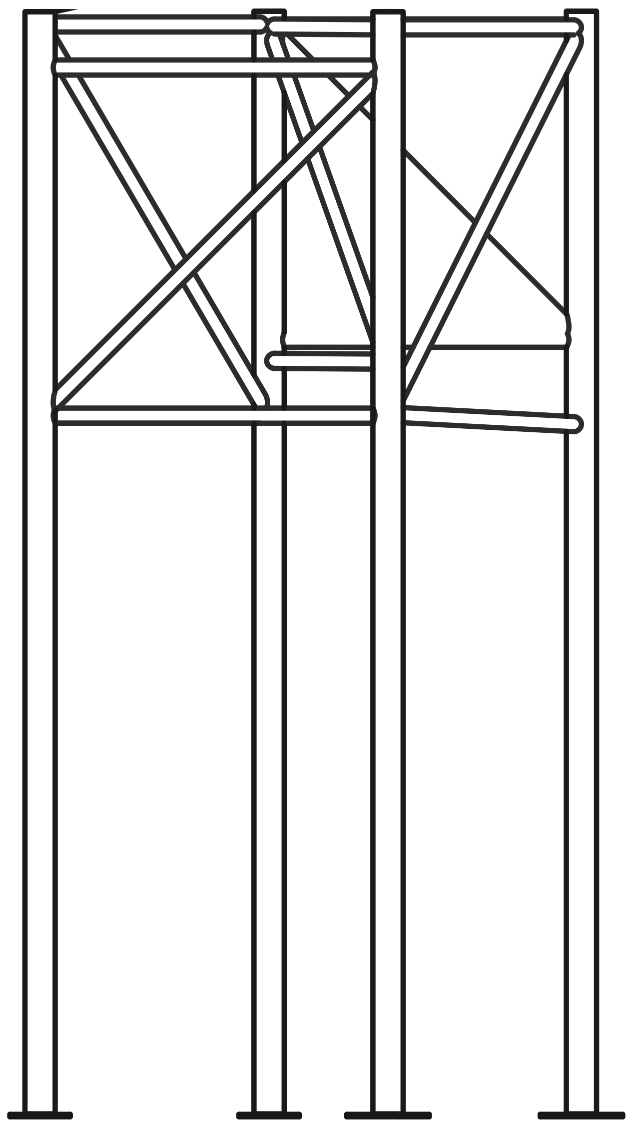

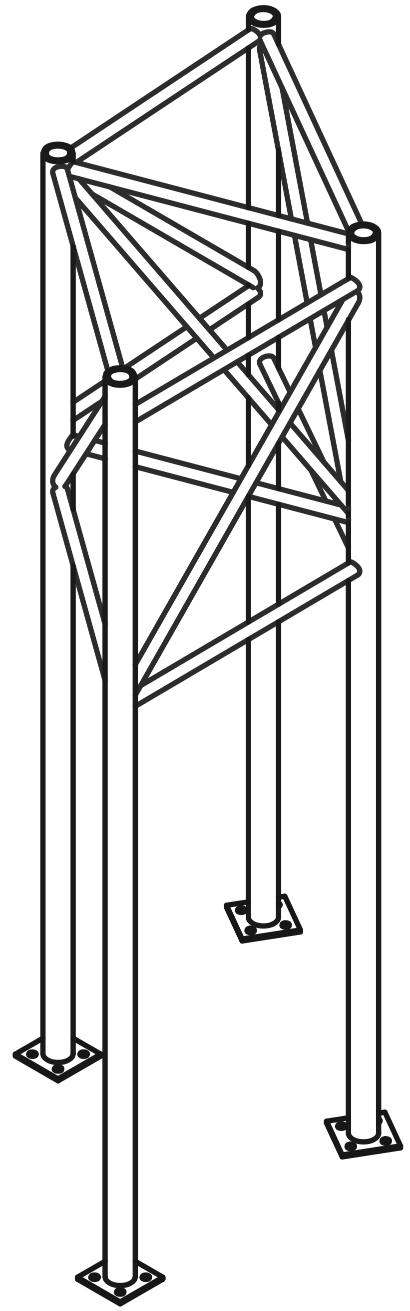

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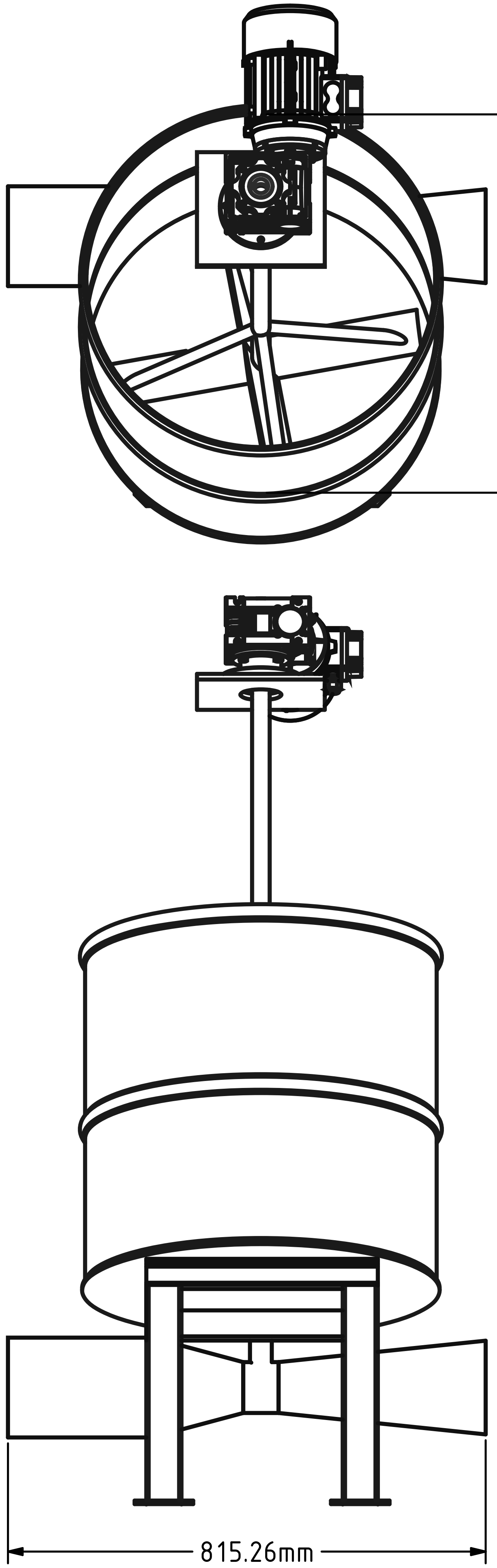

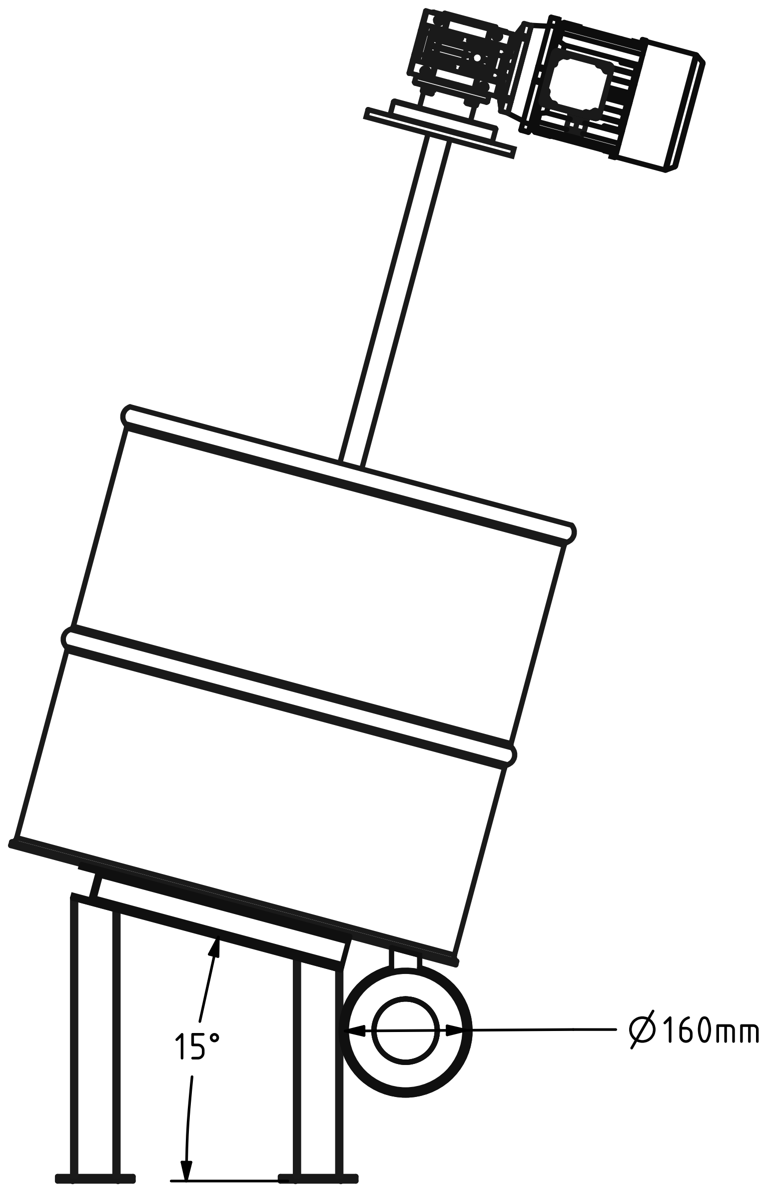

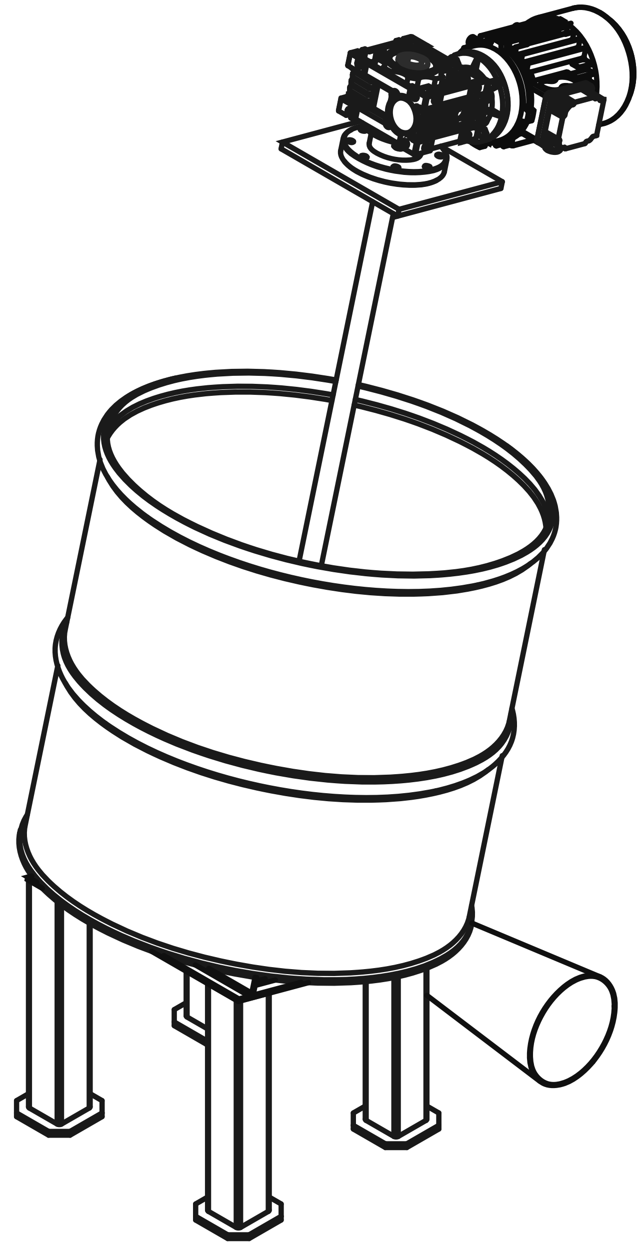

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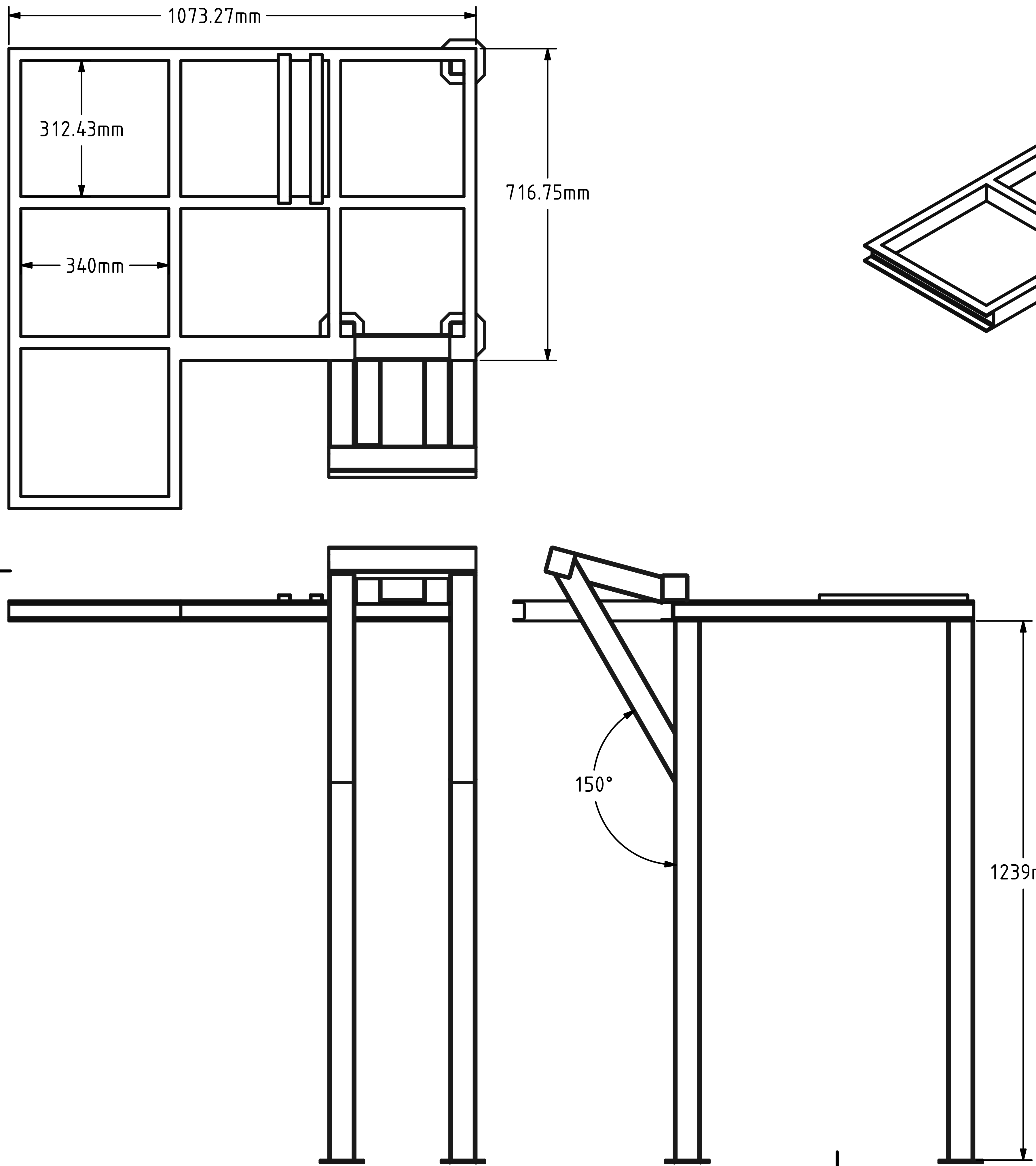

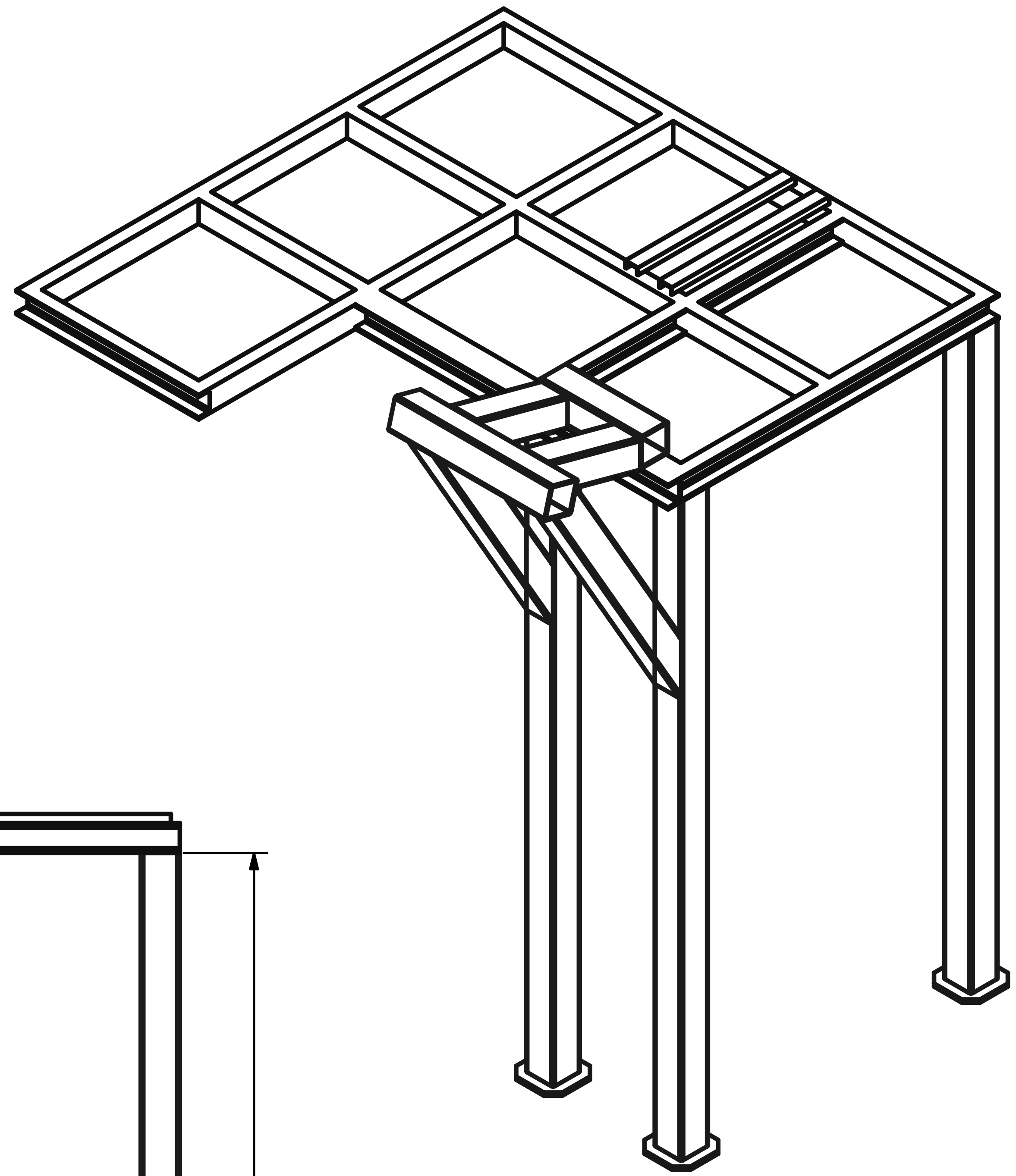

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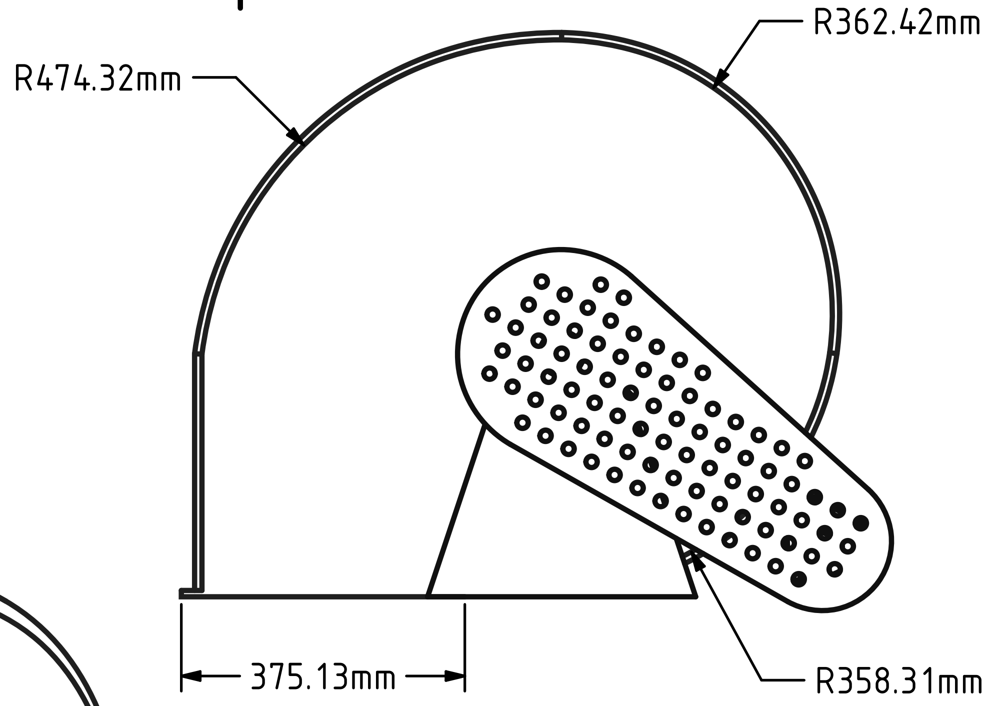

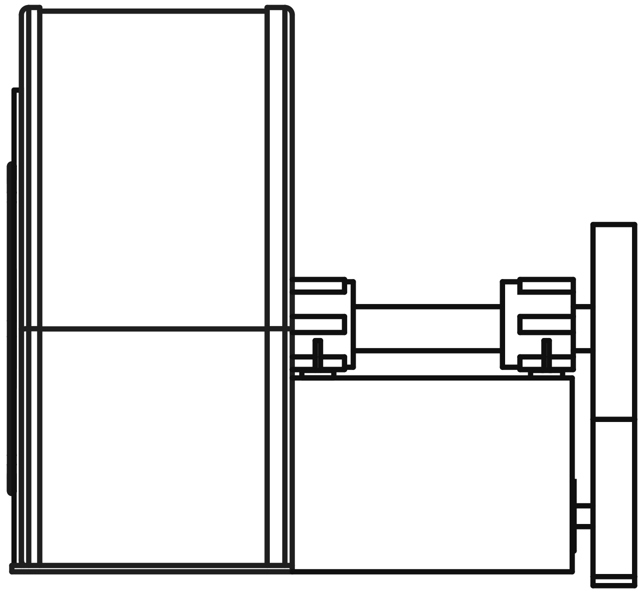

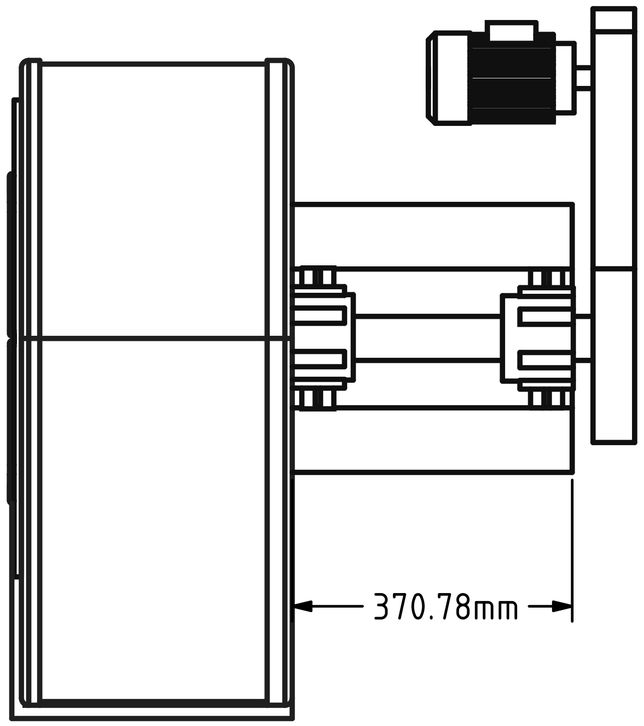

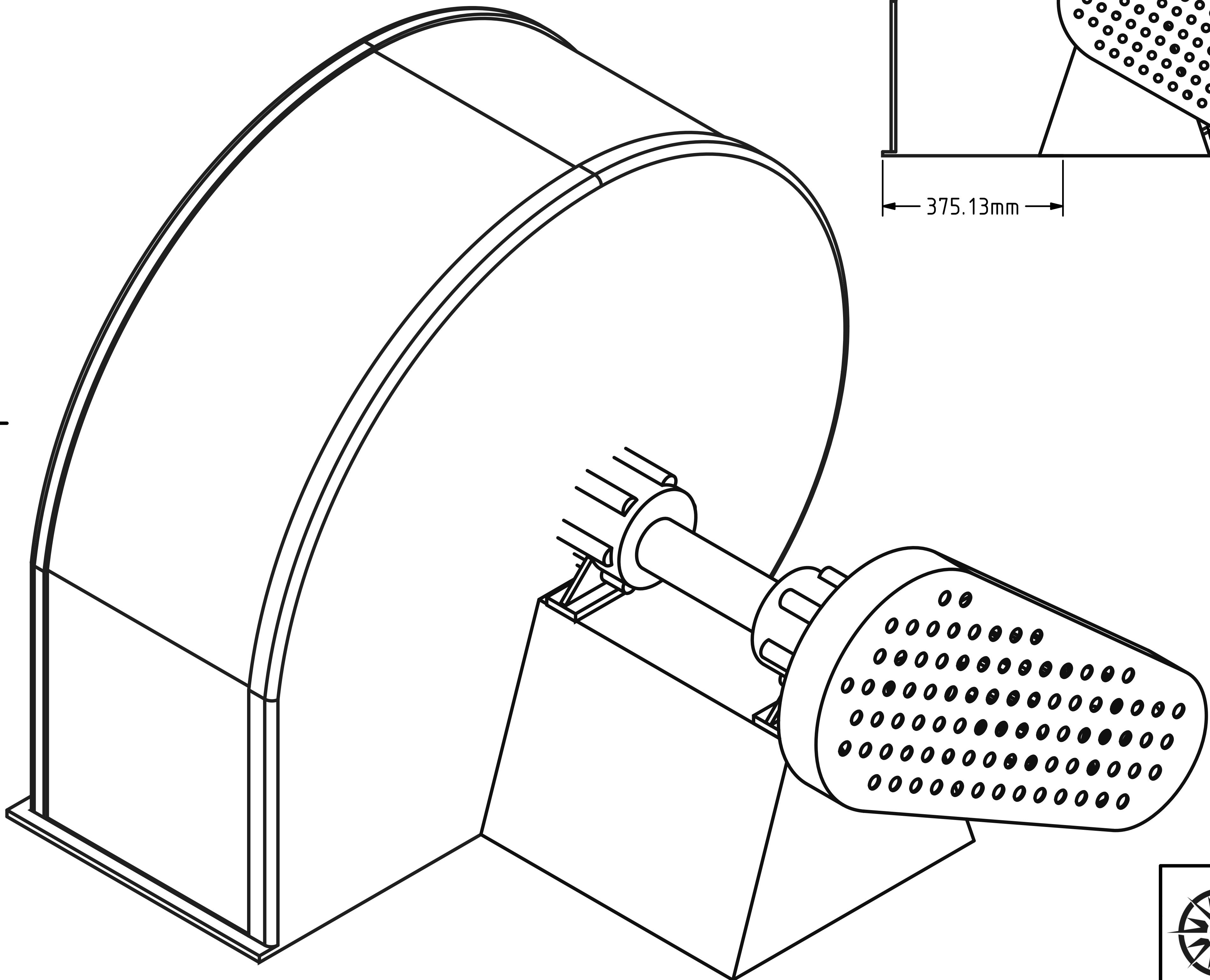

SCALE 1:5

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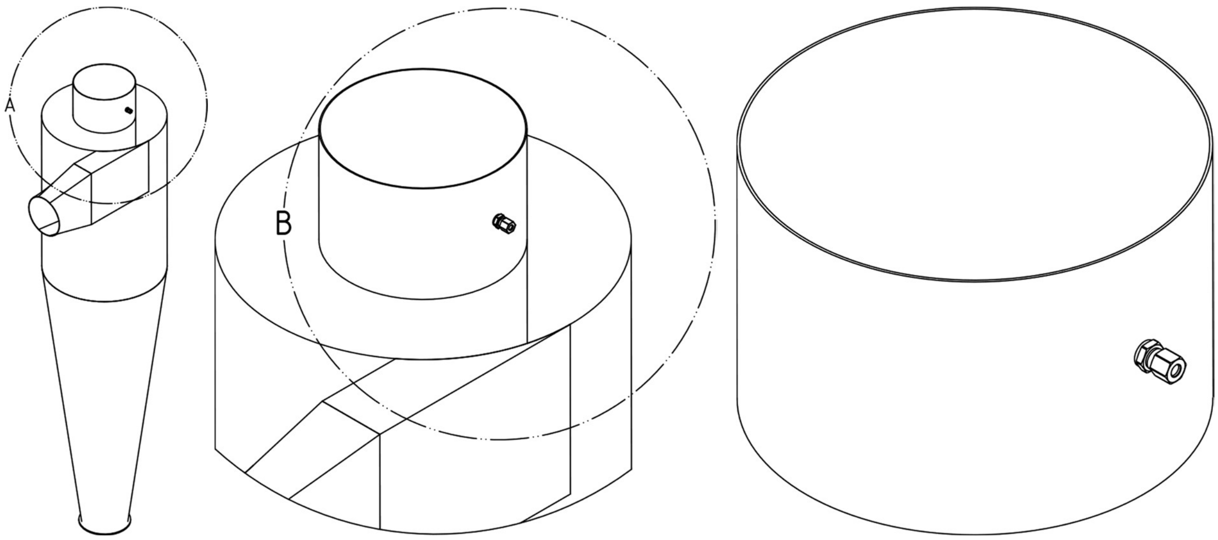
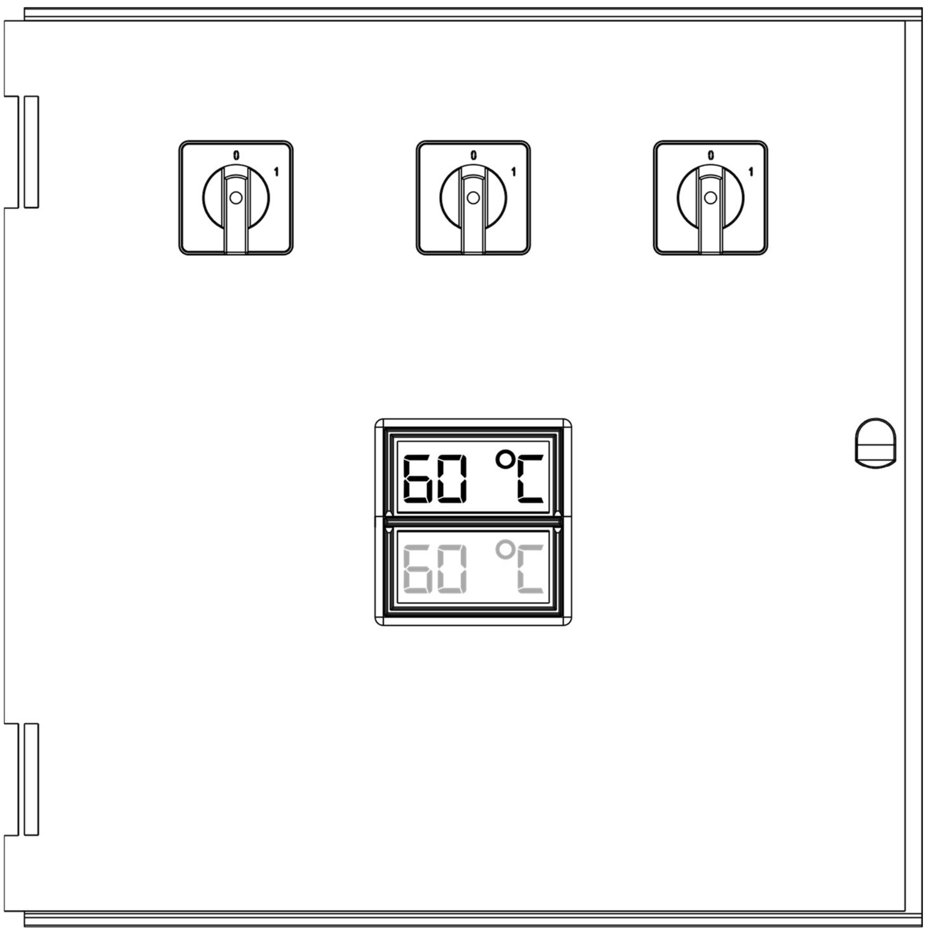
Appendix 2

Placement of temperature sensor that controls the burner

The burner must be thermostat-controlled, and the temperature sensor should be placed at the cyclone air outlet as shown below. A compression fitting should be used to hold the temperature sensor in place.



Temperature should be set at 60 °C.

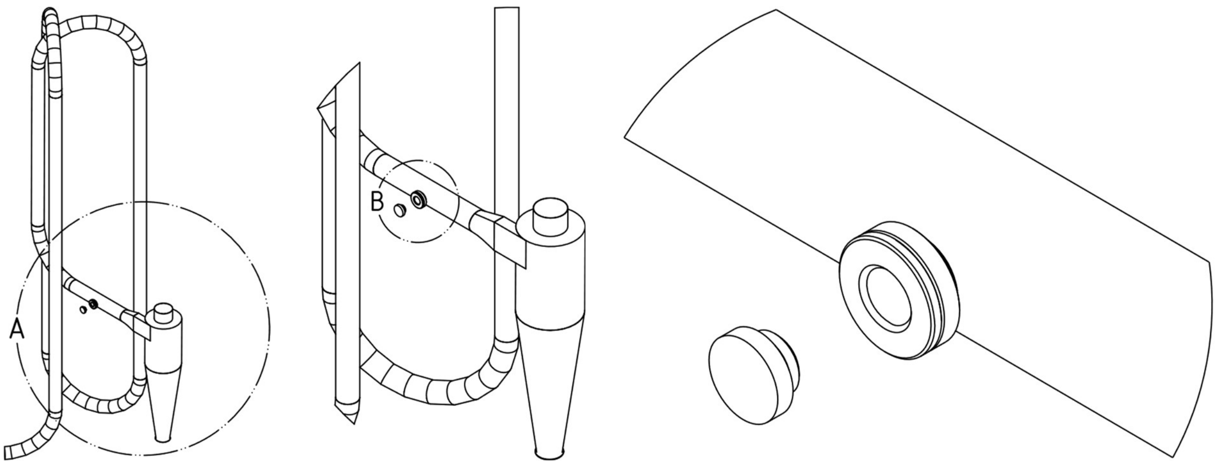


Appendix 3

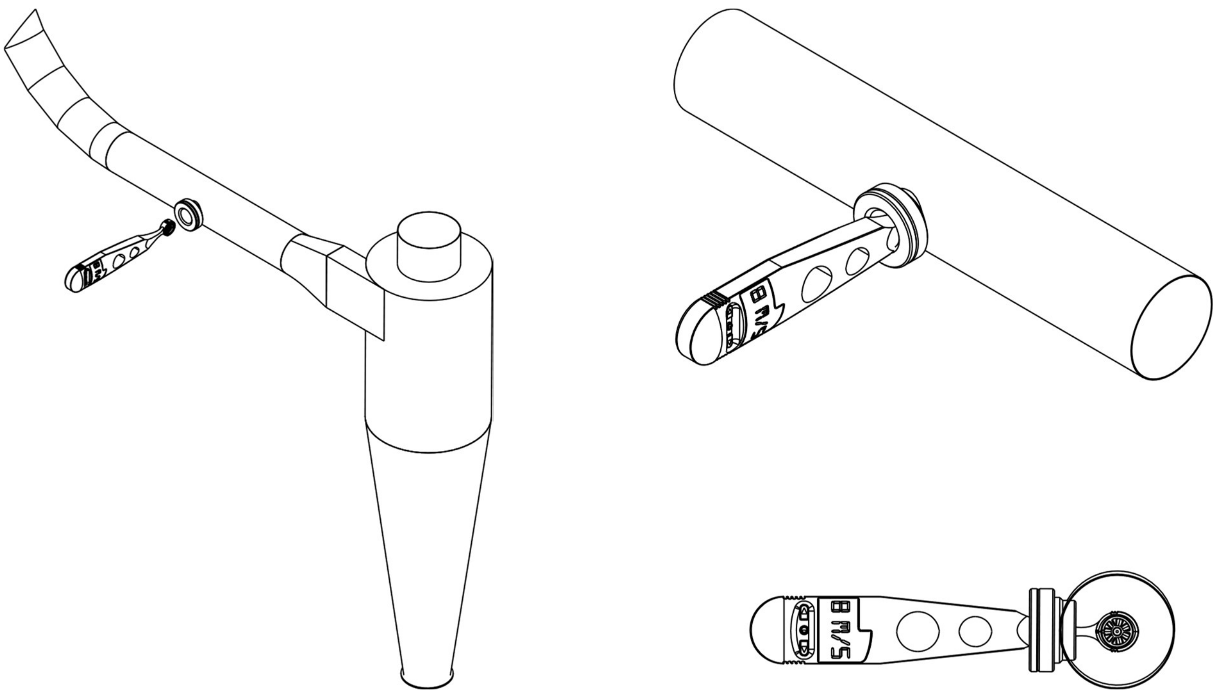
Adjustment of fan speed

This adjustment can only be done once the dryer has been fully assembled.

1. Make an opening at the end of the drying duct and install a fitting. The fitting should be large enough to allow an anemometer to be inserted. The fitting should also have a cap, for closing it once measurements are done.



2. Insert the anemometer and make a reading of the air velocity.



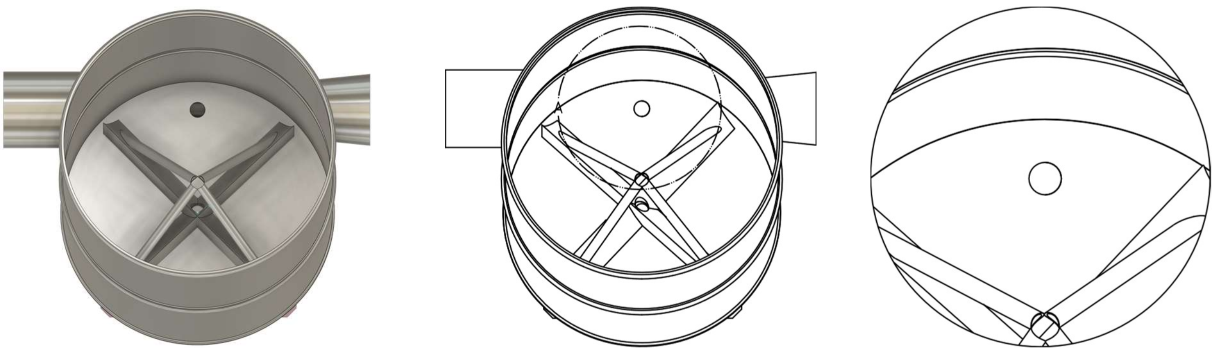
3. Increase or decrease the speed of the fan, by increasing or decreasing the size of the power transmission pulleys, until an air velocity of 8 m/s is achieved.

Appendix 4

Adjustment of the feeding rate

This adjustment can only be done once the dryer has been fully assembled and only after the air velocity has been adjusted (see Appendix 3).

The dryer has been designed to operate with a feeding rate of 325 kg/h (81.25 kg in 15 minutes). The feeding rate is controlled by the orifice opening at the bottom of the feeder, not by the speed of the rotating blade.



1. Prepare enough pre-dried material (sun-dried it until moisture content is 20%$_{wb}$).
2. Using a weighing scale, separate 81.25 kg of material.
3. Run the dryer and add the 81.25 kg of material to the feeder.
4. Measure how long time it takes for the 81.25 kg of material to be fed to the dryer (and the feeder to become empty).
5. If the time measured is less than 15 minutes, reduce the size of the orifice opening at the bottom of the feeder. If the time is more than 15 minutes, increase the size of the orifice opening.
6. Repeat this process until it takes 15 minutes for the 81.25 kg be fed to the dryer.

Appendix 5

Measurements for pneumatic dryer performance evaluation

PREPARATIONS

Feeder calibration

The dryer was designed to be fed 325 kg/h of material at 20% moisture content. The dryer will still work, and the target moisture content might still be reached, if a different feeding rate is used, however, its efficiency will decline substantially, as the dryer will operate out of its design point. Therefore, it is important to perform this calibration and assure a steady feeding rate of 325 kg/h of material at 20% moisture content. The feeding rate is controlled by the rotational speed of the screw or the rotational speed of the plough, depending on the type of feeding system being used. Higher the rotational speed, the higher the feeding rate.

For this calibration it is needed:

- 270 kg of wet cassava grits with a moisture content of 20%wb
- 5 bags (sacks)
- Weight scale
- Stopwatch

Step 1. Divide the 270 kg of wet cassava grits into 5 bags, using the weight scale to make sure that each bag contains 54 kg of product.

Step 2. Add an entire bag (54 kg) to the feeder, and at the same time start the chronometer of the stopwatch.

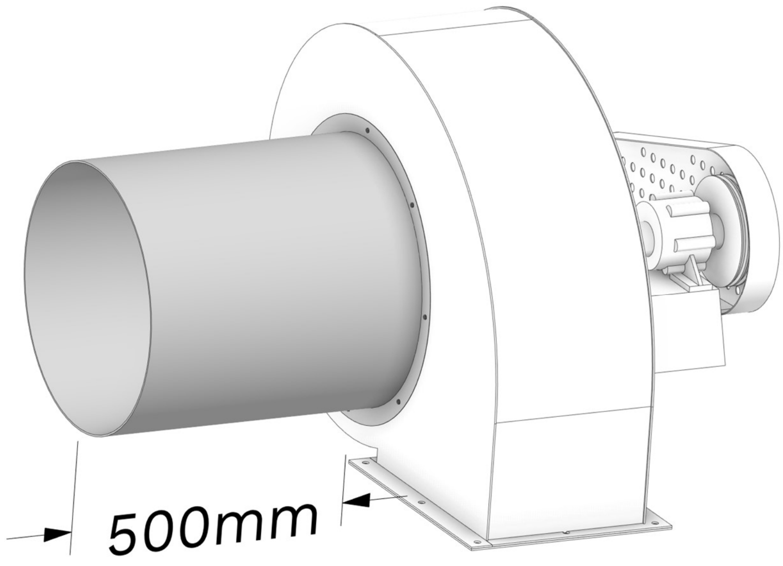
Step 3. At the moment that the feeder becomes empty, stop the chronometer, and note down the time elapsed.

Step 4. If the time elapsed was longer than 10 minutes, increase the rotational speed of the screw or the rotational speed of the plough. If the time elapsed was shorter than 10 minutes, decrease the rotational speed of the screw or the speed of the plough.

Step 5. Repeat this procedure until the rotational speed that makes the feeder empty in 10 minutes is identified. This is the rpm that provides a feeding rate of 325 kg/h. Operate the dryer always at this feeding rate and do not make further changes to the rotational speed of the screw or the speed of the plough.

Duct at fan inlet

To perform air velocity measurements, install a 500 mm long duct at the fan inlet as shown:

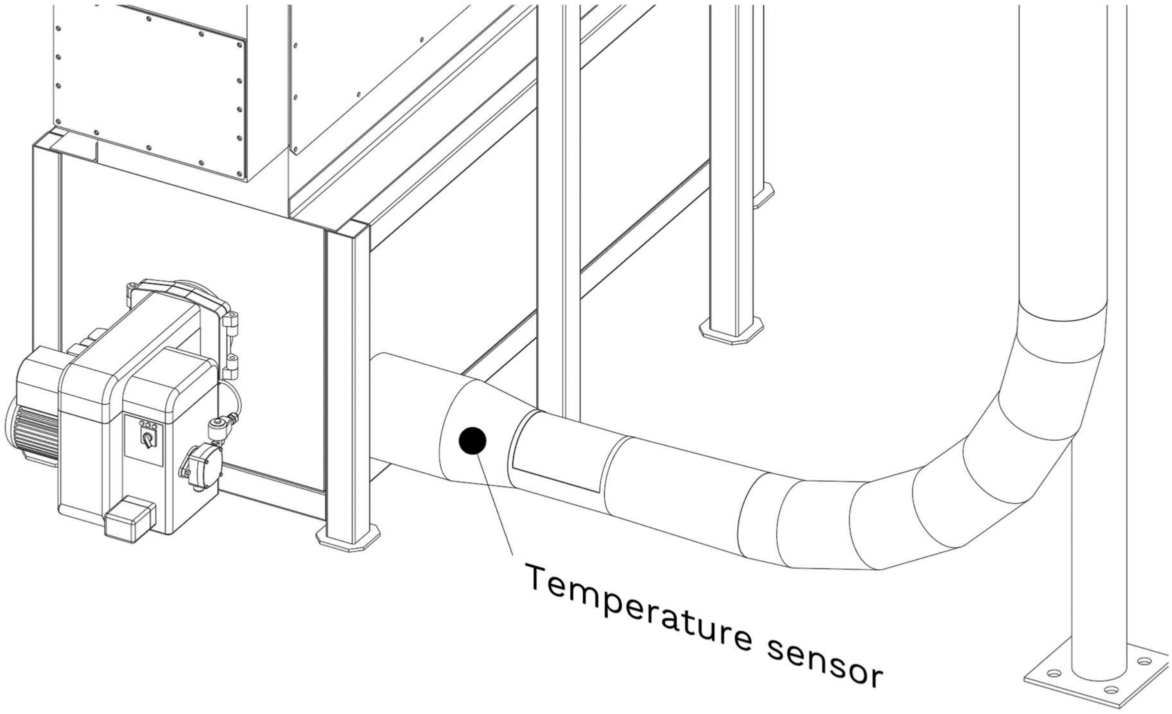


Diesel burner temperature control

Make sure that the burner is thermostatically controlled, and the temperature sensor that controls it’s on/off operation is placed at the cyclone air outlet (see appendix 2 for details).

Dryer inlet temperature

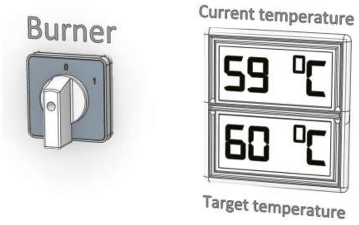
Install a thermometer at the dryer inlet, between the heat exchanger outlet and the feeding point.



DATA COLLECTION

Pre-heating phase

Set the thermostat of the burner to 60 °C as shown.



Switch the fan on and ignite the burner. Let it run for 45 minutes to warm up the dryer. Do not switch the fan off.

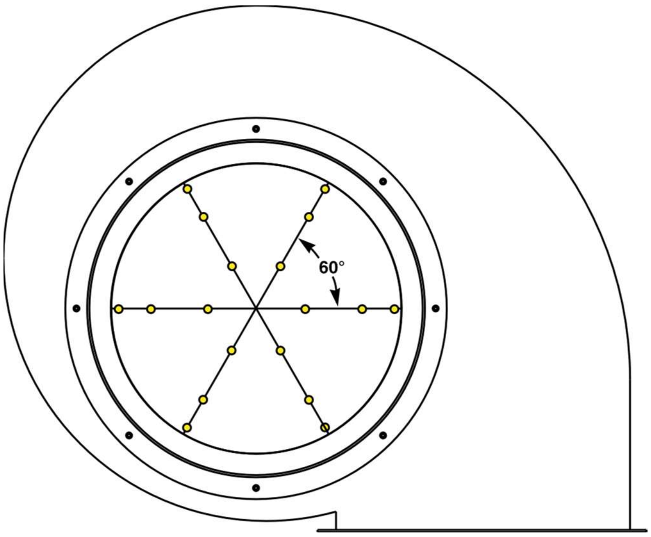
Steady-state phase

Once the pre-heating phase is completed, add material to the feeder and switch it on. Let the dryer operate for another 45 minutes. During this period, make sure there is always material at the feeder.

Measurements

Now that the dryer is operating at a steady-state condition, measurements can be performed. Continue adding material to the feeder, and assure it never runs empty.

- At the fan inlet, perform 18 **air velocity** measurements over the cross-sectional area as shown:



- Record the **temperature** and **relative humidity** of the ambient air.
- Record the **temperature** of the air at the dryer inlet.
- Collect samples of the material at the feeder and measure its **moisture content**.
- Collect samples of the dried material and measure its **moisture content**.

RESEARCH PROGRAM ON Roots, Tubers and Bananas

The CGIAR Research Program on Roots, Tubers and Bananas (RTB) is an alliance led by the International Potato Center implemented jointly with Bioversity International, the International Center for Tropical Agriculture (CIAT), the International Institute of Tropical Agriculture (IITA), and the Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD), that includes a growing number of research and development partners. RTB brings together research on its mandate crops: bananas and plantains, cassava, potato, sweetpotato, yams, and minor roots and tubers, to improve nutrition and food security and foster greater gender equity especially among some of the world's poorest and most vulnerable populations. www.rtb.cgiar.org

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