

## Development and Performance Evaluation of a Laboratory Batch Pulp Digester

Omoniyi, T. E, Onilude, M. A

Department of Agricultural and Environmental Engineering,  
Faculty of Technology,  
University of Ibadan. Oyo State, Nigeria.

Corresponding Author: Omoniyi, T. E

---

### Abstract

Paper production has become a very important aspect of daily life. Presently, most of the paper being used in Nigeria today is imported. The Pulp Digester has been designed and fabricated to enhance the production of paper locally, thereby reducing losses to the Nigerian economy due to foreign exchange. This paper describes an improved directly heated, batch pulp digester built for laboratory use. It consists of the pulping vessel and lid, electrical components and control units, heaters, pressure gauge and timer and the vessel stand. The electrical components maintain precise controls over pulping conditions (time, temperature and pressure) for different pulp activities (pre-steaming, liquor impregnation and cooking). The geometry of the digester, including a 20 litres cylindrical vessel of 10mm thickness securely fixed with heaters and lagged with 50mm thickness of glass fibre and sealed up with a galvanized plate coated with silver colour and a number of peripheral measuring links connected to the lid. The designed capacity is 8kg/day while the maximum pulping efficiency is 62% at 180°C and 6 bar and the optimum liquor concentration used are 50% NaOH, 25% Na<sub>2</sub>S of wood chip mass for a period of 4hrs and the total cost of the equipment is \$173.

---

**Keywords:** pulp digester, liquor concentration, design, efficiency, capacity.

---

### INTRODUCTION

Paper is an important product that its uses cut across all aspects of life and its demand is on increase globally. The single most important piece of equipment in pulp production is the digester. Digesters are capital intensive. In 2000, the cost of a typical continuous digester is about 150 million Canadian dollars. The prevailing economic situation and limited technical capability in Nigeria has made it difficult for such and similar laboratory technical equipment to be imported, installed, operated, and managed (Onilude and Owofadeju 2008).

There is therefore a need to fabricate this standard teaching and research equipment locally at reasonable cost. Kraft pulping, which utilizes a digester, is the common modern chemical pulping process. In digesters, wood chips are cooked with white liquor (sodium hydroxide (NaOH) and sodium sulphide (Na<sub>2</sub>S) to remove lignin from the wood and release individual pulp fibres for further processing. There are two basic digesters: batch digesters and continuous digesters. Batch digesters range from 70 m<sup>3</sup> to 340 m<sup>3</sup> capacity, with a standard capacity of 170 m<sup>3</sup> to 230 m<sup>3</sup> for the modern mills. Batch digesters fall into two categories: directly heated and indirectly heated. The principal operations in batch digesting include chip packing and steaming, liquor filling, slow temperature rise to assure complete liquor penetration of the chips, relief of gases,

cooking at maximum temperature, relief of pressure, and blowing the digester. Each of these operations affects pulp properties and qualities (Smook, 1992). In direct heating, steam is injected through a valve in the bottom of the digester. The difference in temperature between the top and bottom makes the liquor circulate by convection, and hot liquor rises through the middle of the digester, while colder at the top flows down the walls to the bottom where it meets hot stream and is heated. However, there are some disadvantages in direct heating. The cooking liquor becomes diluted with steam condensate, putting an additional load on the evaporators. Also, the heating is non-uniform, resulting in temperature difference in large digesters. Non-uniform heating results in uneven cooking that lowers the quality of the pulp. Indirectly heated digesters require more equipment, including a circulation system with a pump, an external heat exchanger, and a strainer section in the digester walls. Indirect heating with forced liquor circulation avoid dilution and a more uniform temperature profile throughout the digester is achieved (Biermann 1993).

Essentials of Continuous digesters, as represented by the Kamy system, separate the principal operations between different vessels, and between different sections within the digester. A typical continuous digester has the bottom section wider than its top section (the widest has a diameter of 9.15 m). A

typical height is between 60 and 70 m (Gullichsen, 1999). Chip charging and liquor circulation patterns are different. In digesters, washing is also standard in these continuous units. Liquor is removed earlier from the digester, while the chips are removed at the base along with wash liquor. Today over 65% of the world's chemical pulp is produced using continuous systems, with single capacities in excess of 2000 ADT/day (Gullichsen, 1999). The original digester systems have been continuously modified over the years with major improvements, such as 1) HI-HEAT washing, 2) single vessels and two vessel systems, 3) Modified Continuous Cooking (MCC), and Extended Modified Continuous Cooking (EMCC), 4) Isothermal Cooking, 5) atmospheric pre-steaming and 6) Lo-solids cooking (Sandrock and P.L. de Vaal, 2010).

Directly heated batch digester was designed and fabricated because of its flexibility, cheaper price, ease to install, operate, manage and maintain and due to its suitability for teaching and research purposes. The design specification undertaken by the study conform only to laboratory scale aimed at achieving total fibre management but its result is capable of been incorporated in a larger mills. Thus the objective of the study includes production of an improved laboratory, directly heated, batch, pulp digester that is cost effective and suitable for teaching and research and to improve the properties and qualities of the pulp produced.

**MATERIALS and METHODS**

The laboratory batch digester fabricated is expected to solve the non-uniform heating and uneven cooking associated with direct heated batch digesters, non-availability of suitable, efficient teaching and research equipment for pulp digesting, non-provision of volume measurement and estimation during pulping, non-incorporation of sequential operational processes in the instrumentation control, another important goal has been to improve the properties and quality of the pulp produced by batch digester and to reduce high volume of rejects associated with batch digester. The materials of construction were locally sourced.

**Components of the Digester**

The pulp digester is designed to make use of high pressure at elevated temperatures to break the lignocellulosic bonds binding the wood fibers. The components needed are; the vessel and lid; electrical components, pressure gauge and timer and the vessel support.

**GENERAL DESIGN CONSIDERATIONS**

**The Pulping vessel**

Stainless steel plate is used to construct the pulping vessel because it is resistant to corrosion; it has good thermal conductivity and can handle varying acidic

and alkaline conditions as well as elevated temperature and pressures (Woodman, 1993). It is also durable. The vessel is cylindrical with full lid. The cylindrical shape is preferred as it aids convection currents which transfer heat in liquids to disperse well within the vessel, enabling even distribution of temperatures in shorter time as shown in plate3. With full lid, it'll be easier to calibrate the volume of cooking liquor inside the vessel and the lid will be more air-tight. The designed capacity is 20litres and the height is 400mm, hence the inner diameter is approximately 250mm ( $V = \frac{\pi D^2}{4} h$ ). The thickness of the vessel is estimated from the yield strength of thin walled cylinder bearing fluid under atmospheric pressure given as:

$$\sigma_{yield} = \frac{Pr}{t} = 250 \text{ Mpa (Ryder , 2004)}$$

Where, r = radius (185 mm), t = thickness (t), P = pressure (4 bar=4 X 10<sup>5</sup> N/m<sup>2</sup>). Using a factor of safety n = 4 to accommodate forces arising from the action of the lowering mechanism,

$$\sigma_{yield} = \frac{250MPa}{4} = 62.5MPa (6.25 \times 10^7) N/m^2$$

$$= 62.5MPa \equiv 6.25 \times 10^7 N/m^2$$

$$\text{Therefore, } t = \frac{4 \times 10^5 \times 185}{6.25 \times 10^7} = 1.216mm$$

For a thin walled cylinder under increased pressures, a vessel thickness of 10mm is used.

**The lid & Damper**

The material of construction of the lid is stainless steel while that of the damper is rubber. The damper and the lid are shown in Plate1 and 2.

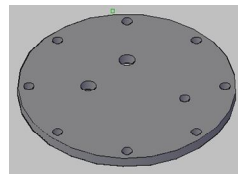


Plate1: Vessel lid

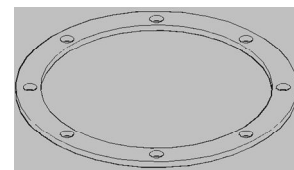


Plate.2. Damper

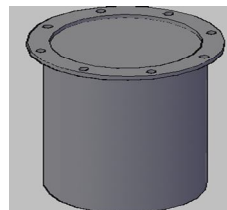


Plate.3. Cooking vessel

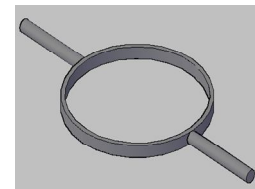


Plate.4: Connecting Shaft

**Electrical Components**

The electrical components used for the pulp digester includes heating elements, thermocouple, thermostat and switch/control box. Two types of heat sources are used. One is a hot plate which is placed beneath the vessel. The other are two bands heaters fixed around the circumference of the vessel, about the mid-

section. This is to ensure even distribution of heat inside the vessel. It has a power rating of 1500watts, 250volts and 4A. The thermocouple used is the k-type with bare tip and glass braided insulation, length is 1.5m, wire diameter is 24gauge and 0.5mm. The insulation used is fibre glass braided with outer dimensions of 2.3 x 1.3mm while the maximum temperature is 500°C. In order to ensure cooking of the wood chips at a constant temperature, an analogue thermostat with variable gauge, having a temperature range of between 0°C and 250°C is used. The control box contains the switches for power control of the heating systems, the meter to the thermocouple and two light indicators: these have colours red and green to indicate the status of the heating systems. RED- OFF; GREEN- ON.

**Pressure Gauge and Timer**

Gauge was mounted on the lid of the vessel. It should be able to read a minimum of 1bar. The vent is included to triggers the battery operated digital timer as the pressure is adjusted to suite efficient recommended cooking pressure. Timer was located directly above the vent, such that when the pressure is corrected to 6 bars, the ‘vented’ air pressure triggers the switch of the timer and this enable the cooking duration to be read directly on the timer as shown in plate 5. Timer specifications are stainless steel test gauge, accuracy class is between 0.25% to 0.4% and recalibration device ranges from 0.1Mpa to 0.6Mpa.

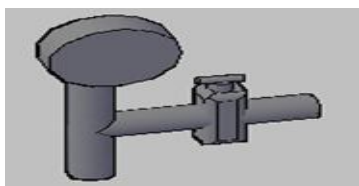


Plate 5 : The pressure gauge

**Vessel Support and Frame Stand**

The stand should be able to support the vessel and its contents. It should also be such that the vessel can be rotated at ±270° (at least) vertically but rigid in the horizontal direction as shown in plate 6,7, and 8.. Metal angle bars of 2 inches thickness are used, cross-braced at intervals towards the base to provide the required support and rigidity for the cooking vessel.

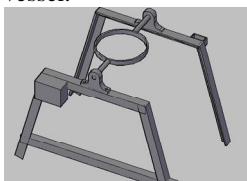


Plate 6: Vessel support

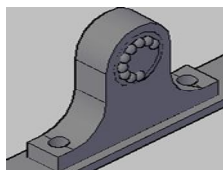


Plate7:Ball bearings

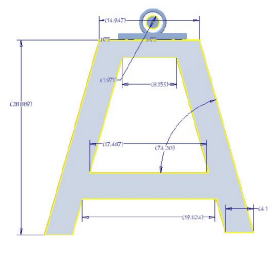


Plate 8: Dimensioning of the vessel support

**Performance Evaluation of the Digester**

*Gmelina arborea* is harvested, debarked and chipped manually. The Chips dimensions are 30 to 40 mm long, 3 to 5 mm thick and 20 to 30 mm wide. The chips were screened to remove both the under-sized and over-sized chips. The over-sized chips are re-chipped while the under-sized ones are discarded. The mass of wood chips varied from 1.0 to 5.0 kg while the mass of dried wood chips were fed into the digester and 10 litres of water added. 0.25 kg of NaOH and 0.13 kg of Na<sub>2</sub>S were added to the mixture of the wood and water in the digester. The digester was covered and securely fastened. Precise controls were maintained over pulping conditions. Pre-steaming of wood took about 15 minutes at 100°C while liquor impregnation was about 45 minutes at between 105 – 130°C. The contents are then heated to approximately 180°C (356°F) to accelerate the delignification reaction for 1.5 – 2.5 hours. The reactions could be expressed according to Sjöström E.(1993) thus:



At the end of the cooking period the digester is switched off and the pressure is vented. The contents are allowed to cool down. The pulp is later separated from the black liquor and washed to reclaim the valuable chemicals. The acceptable pulp is placed in a large container and diluted to low consistency and the tests carried out include determination of the pulping yield, determination of the moisture contents of the pulp slurry, making a standard beater test on the pulp using TAPPI methods T200 and T205 and the physical properties of the pulp produced.

**RESULTS AND DISCUSSIONS**

A direct heated batch digester is fabricated due to its flexibility, ease of operations and low cost. The schematic diagram of the pulp digester is shown in Plate 9.

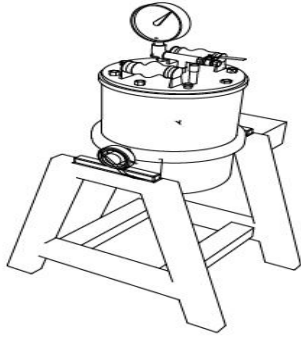


Plate 9: The schematic diagram of the digester

The digester consists of a vessel and some periphery equipment. The vessel is made of carbon steel well lagged with glass fibres to prevent heat loss to the environment. The heating units consist of three heaters each rated 1500 watts; the hot plate is located at the base of the vessel whereas the two band heaters are precisely spaced along the vessel's height to ensure uniform heating. The lid is leak-proof with rubber tyre firmly secured in the slots between the lid and the vessel's top. The lid is also incorporated with monitoring and control equipment that measure record and control various key parameters. Parameters monitored are: the temperature, pressure and quantity of the contents at regular intervals. These are carried out with the help of thermocouple, pressure gauge and steam meter well connected to the lid.

The temperature meter is used to monitor and record temperature of the digester contents, it is calibrated from 0 to 200 °C while the pressure gauge is used to monitor and control the pressure of the digester contents and it is calibrated from 0 to 10 bars. All the necessary metering and monitoring systems are installed in the distributed control units. The instrumentation system is locally designed and calibrated to ensure accurate measurement. These have relays and electrical facilities to set time, temperature and pressure to pre-determined values.

The capacity of the laboratory direct heated batch digester is approximately 20 litres (0.02m<sup>3</sup>) and with a cylindrical shape and a height of 400 mm and a diameter of 250mm. Part of the instrumentation system is the presence of a pressure venting valve that regulates the internal pressure of the vessel. The valve opens automatically to release out excess gases from the inside of the digester whenever the pulping pressure is higher than the desired level.

**Special Features of the Design**

The bottom hot plate and the two band heaters work independently and are properly monitored to ensure uniform heating of the contents in the vessels. The direct monitoring and measurement of quantity of the contents of the digester by steam meter help to improve uniformity and quality of the pulp. The

principal operations are programmed to work in sequence incorporating some flexibilities to achieve total fibre management. The time, temperature and pressure related to chip preheating, steaming, impregnation, penetration and cooking were determined. During the impregnation stage, a retention time of thirty to four-five minutes are introduced at a temperature between 105°C and 130°C, and heating is done only by the bottom hot plate to ensure gradual and consistent impregnation of the wood chips by the white liquor. The heating and cooking of the chips is for a period of between 1 to 2 hours at temperature between 160°C and 180°C. The stand is constructed with the digester having a swinging form for convenient discharge of the contents and for cleaning. The control unit is coupled to the stand with the knobs for automatic/manual temperature, time and pressure measurement to ensure accurate monitoring and control. This is depicted in Plate 10 below.



Plate 10: Pulp Digester

**Time to Pulp**

There was significant difference in the pulping efficiency at different period of time. The optimum pulping time for the constructed pulp digester is about 4 hours. Pre-steaming of wood took about 15 minutes, liquor impregnation about 45 minutes and heating was about 3 hours. This is depicted in fig. 1.

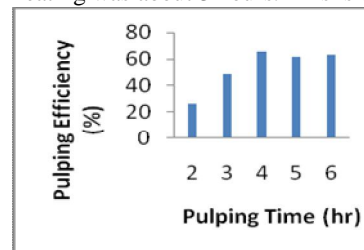


Fig. 1: Pulping Efficiency-Time

**Pressure variation to Pulp Efficiency**

There was also significant difference in the pulping efficiency at different pressure of pulping. The optimum pulping pressure was 6 bars.

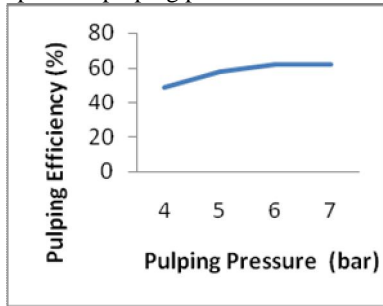


Fig. 2: Pulp Efficiency-Pressure

**Temperature variation to Pulp Efficiency**

The optimum pulping temperature was 180°C

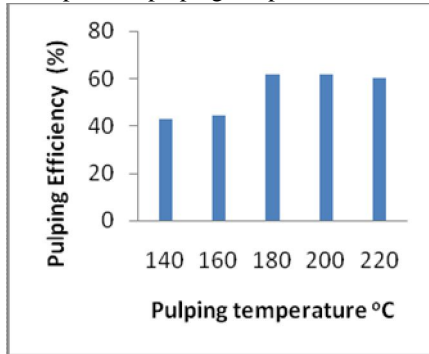


Fig. 3: Pulp Efficiency-Temperature

**Concentration of liquor to Pulp Efficiency**

The optimum liquor concentration is a mixture of 50% NaOH and 25% Na<sub>2</sub>S of the mass of the wood to about a liter of water.

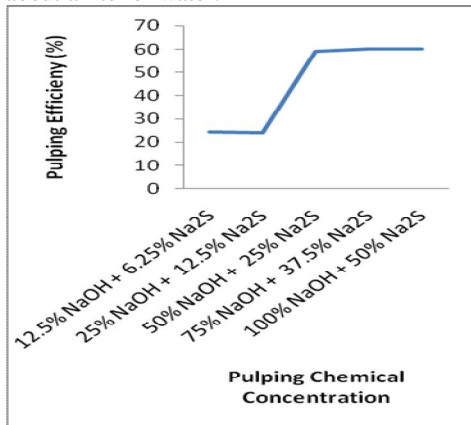


Fig. 4: Pulp Efficiency-Liquor concentration  
Technical evaluation of the pulp

The production capacity and the reliability ratios are 0.73 and 0.85 respectively. Hence the machine efficiency (Product of 0.73 and 0.85) is therefore **0.62** (62%)

**Product Characterization and Quality**

The moisture contents of the pulp slurry from table 4.1 was found to be 41.1%, while the average pulping yield was 47.3%, the bulk density and the true density are 1268.5 and 1349.4 kg/m<sup>3</sup> respectively. The porosity of the pulp slurry was approximately 6.1%.

Items	Cost
The vessels	89,000
The stand	15,000
The controls	30,000
Lagging materials	17,200
Labour	25,500
<b>Total</b>	<b>N 176,700</b>

**CONCLUSIONS**

The batch digester has proved a good substitute for producing laboratory pulp products for teaching and research purposes.

**REFERENCES**

Biermann, Christopher J. (1993). Essentials of Pulping and Papermaking. San Diego: Academic Press, Inc.. ISBN 0-12-097360-X.

Gullichsen, J. (1999): Fiber Line Operations, in Chemical Pulping, Volume 6A, Papermaking Science and Technology, J. Gullichsen and H. Paulapuro, eds., TAPPI/Finnish Paper Engineers' Association, Atlanta/ elsinki, 1999.

Onilude. M.A. and Owofadeju F.K (2008): TWE 522; A lecture note of Pulp and Paper Technology. Department of Agricultural and Environmental Engineering, University of Ibadan.

Ryder G. H. (2004): Strength of Materials, Third Edition, By Macmillan Press Ltd. Reprint of 2004.

Sandrock C. and P.L. de Vaal (2010) Systematic Control Problem Analysis Applied to batch pulp digester control. Department of Chemical Engineering, University of Pretoria.

Sjöström E.(1993). Wood Chemistry: Fundamentals and Applications. Academic Press. ISBN 012647480X.

Smook, G.A. (1992). Handbook for pulp and paper technologists. Joint Textbook Committee of the Paper Industry, 1992.

Woodman, Jocelyn (1993). "Pollution Prevention Technologies for the Bleached Kraft Segment of the U.S. Pulp and Paper Industry (see p 66)" (PDF). U.S. Environmental Protection Agency. <http://www.p2pays.org/ref/5C02/5C01128/01128.pdf>. Retrieved 2007-09-11.