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DESIGN AND EXPERIMENTAL ANALYSIS OF CONDENSER FOR THE PRODUCTION OF BAMBOO VINEGAR

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Abstract – This paper presents methods for the production of Bamboo Vinegar. Bamboo Vinegar is formed on condensation of Bamboo Vapor which is a byproduct of bamboo pyrolysis occurring during the process of production of Bamboo Charcoal. The Paper mentions the conventional practices of producing Bamboo Vinegar and provides detailed study on the development of a condenser of adequate rating and sizing for the production of Bamboo Vinegar. Appropriate assumptions are made in designing the condenser which is a modification of a shell and tube type heat exchanger. The condenser acts as a heat sink improving the yield and quality of bamboo vinegar produced. Designs have been attempted with strong consideration for manufacture and operational cost as the condenser finds application amongst rural people with little or no technical knowhow, therefore simplicity of design is absolutely critical. Experimental results confirm working prototype of condensation system. Improvement over conventional method of production is specified for in this paper.

Keywords *- Condenser; Bamboo Vinegar; Bamboo Charcoal;*

I. INTRODUCTION

In parts of China, North Eastern India, Africa, Central America charcoal and vinegar production from locally available bio mass has been practiced for centuries. Recently it is being used for the large scale production of Charcoal primarily amongst economically backward sections of society and rural communities. Traditional methods of production in an earth pit or mud kiln are followed [1-7]. The yield of charcoal and vinegar is low, the process is crude, wasteful, inefficient and is not standardized. In North East India the production of charcoal has always been is on a limited scale primarily for local consumption and domestic use.

Bamboo is a very fast growing grass, it grows as a wild grass in North East India and is a native to the region. Therefore the production of Charcoal with bamboo is very attractive as it takes only 3-4 years for Bamboo culms to reach adequate height and weight for commercial production of vinegar and charcoal, much lesser time in harvest of starting material for production when compared to charcoal made from other sources. Deforestation can be significantly reduced as charcoal could meet energy demands reducing their reliance on forest firewood for domestic fuel [8-10]. Also the multiple uses of bamboo provide an incentive for local people in the North East of India and in other parts of the world to cultivate bamboo for economic benefits other than production of vinegar and charcoal [11].

The process of making charcoal involves large amounts of volatile matter to be released from the bio mass during the carbonization stage [12]. The condensation of the emitted volatiles during charcoal making from bamboo yields bamboo vinegar. Bamboo Vinegar is a mixture of 300-400 organic compounds in form of aldehydes, alchohols, acetic acid and aromatic compounds [13]. Bamboo Vinegar is used in the making of Anti bacterial and antifungal agents such as deodorants for application to socks, shoes, as reduces foot odor etc. It is slightly acidic in nature making it toxic to bacteria. It is an additive to fertilizer compost in agriculture, used as insect repellant as it has a smoky, sharp, vinegary smell. Small doses of Bamboo Vinegar and Bamboo Charcoal when added to the diet of poultry show improved growth and increased body mass in the animals.

Bamboo Vinegar along with Bamboo Charcoal is also used for water purification in sewage treatment. Charcoal is known to remove poisonous ions such as Lead and Cadmium from water. This is due to its adsorptive abilities owing to its porous microstructure and very large surface area. Bamboo Vinegar aids in purification by acting as an anti bacterial and anti fungal [14-17].

Besides the above mentioned industrial uses for Bamboo Vinegar the most important benefit of this by product in bamboo charcoal making process is that it shows medicinal properties. It has the ability to purify blood, detoxify patches made from bamboo vinegar are known to act as blood purifiers when applied over skin. It is an anti biotic herbal remedy for sore throat and gout improves blood circulation, eliminates inflation and swelling. Bamboo Vinegar is also used in the making of cosmetics as Acetic Acid which is the primary content is known to soften skin [18].

The objective was to design a condenser of appropriate sizing and rating for the production of bamboo Vinegar from a specified mass of raw bamboo. This would not only see the improvement in the process for production with attempt to derive a solution via technical and scientific study but also oversee the standardization of the process.

II. CONVENTIONAL METHODOLOGY OF PRODUCTION OF BAMBOO VINEGAR

The production of Bamboo Vinegar involves the heating of the bamboo to temperatures as high as 300°C-400°C. Heating of raw bamboo (bio mass) over 250°C causes the volatile content of the raw bamboo to be emitted from the bamboo as it undergoes dry distillation/pyrolyis. The volatile content emitted comprises of bamboo gas (non condensable part), bamboo vapor (condensable part). The condensation of the bamboo vapor results in formation of bamboo vinegar [18, 19].

The traditional method of production of bamboo vinegar here in North Eastern India involves loading the raw bamboo into a horizontally placed oil drum. The raw bamboo 3-4 years old is cut to around 80cm length and placed into the oil drum. The oil drum is placed horizontally and covered with 1 feet of earth insulation. The oil drum acts as the pyrolysis chamber for the bamboo. Oil Drums are preferred for the process as they are cheap, easily available and provide moderately air tight sealing essential for pyrolysis process. The drum opening is sealed by mud plastering and covered with metal sheets. Two small orifices are left open for passage of heated gases from combustion chamber as shown in Fig. 1a. The combustion chamber for the production of heated gases is built adjacent to the drum orifice opening, with bricks that are mud plastered to build the combustion chamber as shown in Fig.1b.

(a) (b)

Fig.1 : Setting up of Charcoal production unit in traditional method of production: (a)Metal sheets cover opening,oricesprovided for heated gas enters into pyrolysing chamber in Tura (b) mud plastering and using bricks to make combustion chamber

The production unit is now fired as shown with firewood as fuel for the generation of heated gases to be passed over the bamboo in the oil drum as shown in Fig. 2a. The exit point for gases from the oil drum is as shown in the Fig. 2b.

(a) (b)

Fig. 2 : Traditional method of charcoal in operation: (a) Traditional bamboo charcoal furnace being fires during daylight hours. (b) Opening on the other side of the Oil Drum for exit of gases of combustion and volatile matter formed on degradation of bamboo and collected bamboo tar.

The flue gases from the combustion of firewood and emitted gases from the pyrolysis of bamboo exit though the opening to be diverted into a hollow bamboo shaft by an inverted funnel arrangement.

The bamboo shaft used for condensing is prepared by cutting out the nodes and wrapping the nodes with moist jute packing. The jute is kept constantly moist and the hollow bamboo shaft now acts as a simple condenser for the production of bamboo vinegar. The shaft is around 18 feet in length and set at an angle of 30° with respect to the ground as shown in Fig.3.

Fig. 3 : Hollow Bamboo Shaft covered with moist jute packing used as condenser for producing bamboo vinegar

III. IDENTIFIED DRAWBACKS OF THE CONVENTIONAL METHODOLGY OF PRODUCTION

The method of condensing bamboo vapor in a hollow bamboo shaft with moist jute packing is unscientific, inefficient and crude. The process of preparation of the hollow bamboo shaft is labor intensive and time consuming as the shaft is of considerable length and all work involved in the preparation of the shaft is done manually.

The heat exchange taking place across the surface of the bamboo shaft is poor as the material conductivity of bamboo is very low. The system is an open system with the inverted funnel arrangement used to divert gases from the exit of the pyrolysis chamber into the hollow bamboo shaft. The entry point to the condenser is not sealed hence a major proportion of the bamboo vapor is lost uncondensed to the atmosphere.

The bamboo shaft though which the condensable bamboo vapors and gases escaping the pyrolising chamber pass requires regular attention to be kept moist for condensation of vapor to take place making the process of production problematic. A single shaft can be used for a maximum of 3 cycles of production before the heat from the gases passing through the shaft causes the bamboo to crack rendering that shaft useless and a new shaft has to be prepared for bamboo vinegar production.

Therefore the yield of bamboo vinegar is low and the process of production time consuming and problematic. The requirement for an adequate condenser for Bamboo Vinegar production can be clearly seen.

IV. ASSUMPTIONS MADE IN THE DESIGN OF CONDENSER

The challenge in designing a condenser for the production of Bamboo Vinegar is that Bamboo Vinegar is a mixture of 400 organic liquids, the composition various with speed of cycle for production, seasonal conditions, stage in the cycle for production, type of bamboo used in terms of species and age hence no fixed values for latent heat of enthalpy is available.

The best possible approach to solve the problem of rating of the heat exchanger was to consider identical mass flow rate of steam under atmospheric pressure at same inlet temperature as recorded from field survey at the unit for production of bamboo vinegar. The recorded inlet velocity of gases for condenser is the same as exit velocity of gases from the pyrolysis chamber. Temperature readings at exit of pyrolysis unit are shown in Table 1. The maximum temperature recorded during cycle for production is used in the design of the condenser.

By setting a suitable upper limit for designing the condenser we attempt to surely achieve a successful prototype/design of a bamboo vinegar condensation system. The condenser is designed with the assumption of same mass flow rate of steam in place of mixture of bamboo gas, flue gases from combustion and bamboo vapor. The unit is designed for successful operation even at maximum recorded inlet temperature.

The optimization of the designed condenser would be attempted via field testing and experimentation procedures

V. ANALYTICAL CALCULATIONS FOR RATING AND SIZING OF HEAT EXCHANGER

The condenser is designed with the aim to completely condense superheated steam flowing through its tubing. The surface area of tubing over which heat exchange is expected to occur must be sufficient to condense all steam flowing through piping. The mass of water inside the tank on shell side must be adequate for the condenser to act as a heat sink requiring no flow of fluid on shell side. Calculation of mass flow rate of steam through tubing is calculated with the below formula [20].

$$m = \rho_{steam} \times A_c \times v = (.597 \times .00202 \times 0.2)$$

$$= 0.000242 \text{kg/sec}$$

The density of steam is taken at 100°C; therefore the mass flow rate evaluated is higher than in possible actual case where the steam enters the condenser at super heated condition at a temperature of 345°C where the density is correspondingly lower.

Heat Transfer per second in condenser due to condensation of steam is calculated in the following formula [20].

$$Q = m \times (L + C_p \times \Delta T + C_{ps} \times \Delta T_s)$$

$$= 546.92+75.86+115.9= 738.70 \text{ Joules/sec}$$

Average Two Phase Heat Transfer Coefficient Calculations [20] profile for Two Phase flow shown in Fig.4.

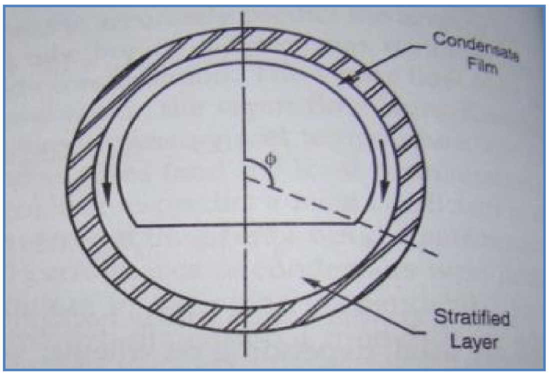

Fig. 4 : Profile for two phase fluid flow through piping

Working Equations by Cavallini and Zechin

$$h_{tp} = 0.05\times(Re_{eq}) \times 0.8\times(Pr_l\times 0.33) \times k_l/d$$

Equivalent Reynolds Number evaluated for two phase fluid flow taking place inside tube side of condenser

$$Re_{eq} = Re_v\times (\mu_v/\mu_l)\times(\rho_l/\rho_v) \times 0.05 +Re_l$$

Liquid Reynolds Number is calculated for fluid flowing in Liquid state with the formula stated below

$$Re_l = G(1-x)\times d/ \mu_l$$

Vapor Reynolds Number is calculated for fluid flowing in gaseous state with the formula mentioned below

$$Re_v = Gxd/\mu_v$$

The material used in the construction of the tubing of the condenser is copper which has high thermal conductivity therefore temperature difference between the wall and the fluid is not significant along the tube. Equation by Cavallini and Zechin can be used provided thermal physical properties and temperature difference between the wall and the fluid do not vary considerably along the tube.

The Reynolds number for liquid phase flowing through tubing is evaluated to be $Re_l = 0.131$, The Reynolds number for gaseous phase is evaluated as $Re_v = 5.126$. Therefore the equivalent Reynolds number for two phase fluid flow taking place inside the condenser is given by $Re_{eq} = 5.53$. Thus the evaluated "Two Phase" heat transfer coefficient for pure steam is given by $h_{tp} = 6.44$.

Rate of Heat Transfer due to condensation of steam is equal to the rate of heat transfer across tube wall via conduction. The equation of Heat Transfer used in designing the condenser and evaluating the number of tubes and required surface area for heat transfer to occur is $Q = h_{tp} \times A_s \times (T_b-T_w) = M \times C_p \times (\Delta t)$. The temperature rise for the mass of water on the shell side is calculated to be $\Delta t = 0.65°C$. Therefore rise in temperature of water on shell side is almost negligible and condenser acts as a heat sink. The value is calculated by equating the Rate of Heat input into the Water on shell side to the Rate of Heat Transfer per second due to condensation of steam.

The required surface area for heat transfer and condensation of all steam flowing inside tubing is calculated to be $A_s = 0.36 \text{ m}^2$. The number of tubes required is calculated by the $\pi \times d \times L \times N = 0.15961 \times (N) = 0.3$. The minimum number of tubes required is calculated to be N=3.

However 6 tubes are provided in the developed prototype as shown in Fig. 5, the precaution is taken to account for the excessive amount of fouling taking place inside the tubing of the condenser. The fouling caused by formation of bamboo tar is shown in Fig. 2b. It is almost impossible to predict the effect of fouling on the heat transfer coefficient and result of heat exchange in the condenser. Therefore optimization of the design was to be attempted by experimentation.

The condenser designed according to the above assumptions and calculations is surely expected to condense bamboo vapor to yield bamboo vinegar because the actual rate of heat transfer will be much lower than evaluated with flow of pure steam. The gas flowing through the piping is a mixture of bamboo vapor (condensable part) and bamboo gas (non condensable part) also the value for latent heat of enthalpy for bamboo vinegar is lower than water.

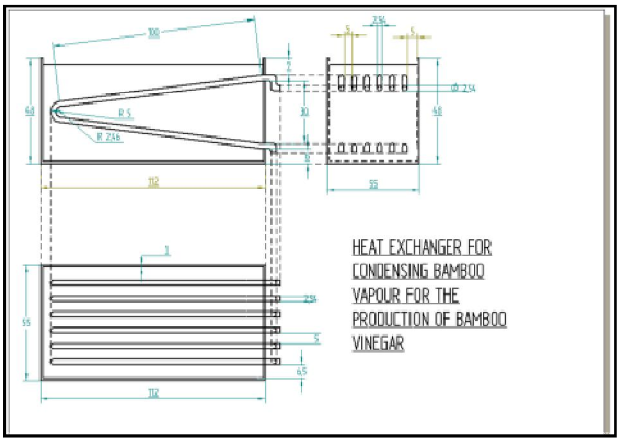

Fig. 5 : Drawing of Condenser.

The flow of gas taking place through the tubing is due to natural convection. If the piping length is too long it will cause stagnation of gas within the piping. Therefore to ensure adequate non restricted laminar flow of gas through tubing pressure drop due to friction losses were calculated. Considering fluid flow combination of 50% steam and 50% Carbon Dioxide (CO_2) the average density is calculated to be

$$\rho_{av}= 1/2\times\rho_{CO2}+1/2\times\rho_{steam}=0.995 kg/m^3.$$

The average viscosity is denoted by

$$\mu_{av}=1/2\times\mu_{CO2}+1/2\times\mu_{steam} =2.455\times10^{-4}.$$

The average Reynolds number is calculated to be

$$Re_{av}=\rho_{av}\times v\times d/\mu_{av}=21.21.$$

The friction coefficient over the length of the piping is evaluated as $f=64/Re_{av}=3.017$. Therefore pressure drop for laminar flow is calculated to be $\Delta p=f\times4\times L/d\times \rho_{av} \times0.5\mu_{av}^2$ =19 Pascal=19×10-5 bar. The evaluated pressure drop of 19 Pascal is negligible, therefore the flow of gas through the piping should be smooth and unrestricted. The values used for symbols used in calculation are given in TABLE I.

TABLE I : MEANING OF SYMBOLS USED AND THEIR VALUES

Symbol	Meaning/Definition	Value
ρ_{steam}	Density of Steam	0.597 Kg/m^3
A_c	Area of Cross Section of Tubing	0.0003629025 m^2
v	Inlet Velocity of Steam	0.2m/s
C_p	Specific Heat Capacity of water	4.187 kJ/kg-K
C_{ps}	Specific heat capacity of steam	2.09 kJ/kg-K
ΔT	Temperature difference through which water is cooled	75^0C
ΔTs	Temperature difference through which steam is cooled	315^0C
ρ_{CO2}	Density of Carbon Dioxide	1.4 Kg/m^3
μ_{CO2}	Viscosity of Carbon Dioxide	0.000012 Kg/(s.m)
μ_{steam}	Viscosity of Steam	0.000467 Kg/(s.m)
f	Friction Factor	3.017
l	Length of Piping	2m
d	Diameter of piping	0.0381m
T_b	Temprature of Bulk Fluid	340^0C
T_w	Temperature of wall	25^0C
M	Mass of water on Shell side	270 kg
L	Latent heat of Enthalpy of steam	2260kJ/kg

VI. CONSTRUCTIONAL FEATURES OF BAMBOO VINEGAR CONDENSER

The body of the condenser is built with GI sheet (shell side) by bending and riveting. Large exposed surface of GI sheet enables easy loss of heat into the environment. The tubing is constructed out of copper. Joints are made water tight with Epoxy compound used for sealing applications. Tap is provided at the rear for easy draining out of the water. Header for the Condenser is built out of GI-T sections of 1.5-inch diameter. T-Sections are joined by welding to construct header for condenser. Attachment of inlet of condenser to exit of furnace is made with GI piping of 1.5-inch diameter.

VII. EXPERIMENTATION AND TESTING OF CONDENSER FOR PRODUCTION OF BAMBOO VINEGAR

The developed prototype condenser was tested at Bethany Society in Shillong to check if the designed condenser was capable of condensing bamboo vapors to yield bamboo vinegar. The condenser was attached to the opening of the conventional furnace as shown in Fig. 5.

Fig. 6 : Testing of Condenser in Shillong.

The condenser was tested only for duration of 4 hours and not for the entire cycle of production lasting 3 days. The primary objective of the preliminary testing was to ensure the adequate rating of the condenser for production of bamboo vinegar, not optimization of the design or checking for improvement by comparing yield.

The condenser was finally installed at IIT Guwahati, attached with the newly developed furnace for bamboo charcoal production as shown in Fig. 6. Rigorous experimentation was now performed by a total of 4 sets of production cycles. The objective of experimentation now was to check for improvement in process of production of bamboo vinegar and also optimize the design via experimentation. The produced Vinegar was collected in glasses at the exit of the condenser and the vinegar was poured out at regular intervals.

The methodology to be adopted for optimization of the design was to run a complete cycle with varying number of active tubing. The number of active tubing was to be varied by plugging the exit of the tubing with cork. The production cycle was to me run initially with all 6 tubes active. The next cycle was to be run with 5 tubes active and 1 tube deactivated by plugging with cork. Then the next cycle with 4 active tubes and 2 blocked tubes, the pattern is to be followed till change in the net yield of bamboo vinegar is observed.

Fig. 7 : Setup of Condenser at IITG by fitting to developed furnace

VIII. RESULTS AND DISCUSSIONS

The first drops of bamboo vinegar formed is shown in Fig. 7a during preliminary testing in Shillong proved that the rating of the newly developed condenser to be adequate for the production of bamboo vinegar. Uniform non restricted laminar flow of gas through the tubing is observed under influence of natural convection as shown in Fig. 7b. Experimentation at Indian Institute of Technology Guwahati for 4 cycles of production yielded the following results. As shown in TABLE II.

(a) (b)

FIG. 8 : Testing of Condenser: (a) First drops of bamboo vinegar condensate. (b) Laminar flow of gas through tubing

TABLE II : RESULTS OF EXPERIMENTATION WITH BAMBOO VINEGAR CONDENSER

Cycle Number	Volume of Vinegar collected (liters)	Mass of raw bamboo being pyrolysed (Kg)	Duration of Cycle (hh:mm)	Number of Active Tubes	Number of Tubes blocked
1st cycle	3.0	33.8	11:00	6	0
2nd cycle	3.1	34	11:40	5	1
3rd cycle	3.0	34.4	11:20	4	2
4th cycle	2.3	34	12:00	3	3

The temperature of the water and atmospheric temperatures were recorded at various instances during production cycle and there is no significant rise in the temperature of the water caused due to heat exchange of the condensing bamboo vapor and cooling of the gases. Rigorous experimentation with the condenser at IITG shows the minimum number of tubes required on the condenser with present configuration of (2 pass 1m length tubing) for condensation of all possible vapor content from the mixture was 4. If number of active tubing if reduced below 4 results in notable change in the yield of bamboo vinegar produced.

The bamboo vinegar produced with new condenser indicates Acetic Acid content of 0.068g/ml or 7.1% by weight in Bamboo Vinegar compared to Acetic Acid content of 0.0394g/ml or 4.11% by weight in Bamboo Vinegar produced with conventional methodology.

The production cycle is run for slightly varying durations but this does not alter the yield of bamboo vinegar as the volatile contents are emitted during an intermediate period in the production cycle that is during the carbonization stage of bamboo. The carbonization stage marks the peak in the process of pyrolysis of bamboo with maximum gaseous and volatile emissions during this phase of production; this phase precedes the completion of the cycle by 2-3 hours.

The small time variations in the production cycle have negligible effect of the bamboo vinegar produced.

The bamboo vinegar produced with the new method of production shows greater acetic acid content than bamboo vinegar produced by traditional method. This process of carbonization with the new process is more efficient with greater degree of conversion of raw bamboo to charcoal. Greater quantities of volatile matter are emitted and are condensed to produce Bamboo Vinegar. Loss of bamboo vinegar to the atmosphere is minimized as the system for condensation of bamoo vapour is now closed. The yield of bamboo vinegar is higher per kg of raw bamboo when compared to the traditional methodology of production of bamboo vinegar with use of the bamboo vinegar condenser.

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