DEVELOPMENT AND EVALUATION OF BIOMASS BASED COMPOSITE WATER HEATER AND DRYER

A thesis submitted to the

Dr. BALASAHEB SAWANT KONKAN KRISHI VIDYAPEETH
DAPOLI
Maharashtra State (India)

In the partial fulfillment of the requirements for the degree of

MASTER OF TECHNOLOGY
(AGRICULTURAL ENGINEERING)
in
RENEWABLE ENERGY SOURCES

by

MISS. Namrata Chintaman Gawali

Under the guidance of

Dr. A. G. Mohod
Associate Professor

DEPARTMENT OF ELECTRICAL AND OTHER ENERGY SOURCES,
COLLEGE OF AGRICULTURAL ENGINEERING AND TECHNOLOGY,
Dr. BALASAHEB SAWANT KONKAN KRISHI VIDYAPEETH,
DAPOLI- 415 712, DIST. RATNAGIRI, M. S. (INDIA)

August-2013

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Approved by the advisory committee

Dr. A. G. Mohod
(Chairman and Research Guide)

Dr. Y. P. Khandetod
(Committee Member)

Er. R. M. Dharaskar
(Committee Member)

DEPARTMENT OF ELECTRICAL AND OTHER ENERGY SOURCES,
COLLEGE OF AGRICULTURAL ENGINEERING AND TECHNOLOGY,
Dr. BALASAHEB SAWANT KONKAN KRISHI VIDYAPEETH,
DAPOLI- 415 712, DIST. RATNAGIRI, M. S. (INDIA)

August-2013

CANDIDATE'S DECLARATION

I hereby declare that the experimental work and its interpretation of the thesis entitled "Development and evaluation of biomass based composite water heater and dryer" or no part thereof has been submitted for any other degree or diploma of any University, nor the data have been derived from any thesis/publication of any University or scientific organization. The sources of material used and all assistance received during the course of investigation have been duly acknowledged.

Place: CAET, Dapoli **(Miss. Gawali Namrata Chintaman)**

Date: / / 2013 (Reg. No. 055/2011)

Dr. A.G. Mohod
B.Tech. (Agril. Engg.), M. Tech. (Energy Management), Ph.D. (RES)
Associate Professor
Department of Electrical and Other Energy Sources,
College of Agricultural Engineering and Technology,
Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth,
Dapoli- 415 712, Dist. Ratnagiri,
Maharashtra, India.

CERTIFICATE

This is to certify that the thesis entitled **"Development and Evaluation of Biomass Based Composite Water Heater and Dryer"** submitted to the Faculty of Agricultural Engineering, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli, Dist. Ratnagiri, Maharashtra State, in the partial fulfillment of the requirements of the degree of **MASTER OF TECHNOLOGY (AGRICULTURAL ENGINEERING)** in **RENEWABLE ENERGY SOURCES** embodies the results of ***bonafied*** research work carried out by **Miss Namrata Chintaman Gawali** under my guidance and supervision and no part of the thesis has been submitted for any other degree, diploma or publication in any other form. She has duly acknowledged all the assistance and help received during the course of investigation.

Place: CAET, Dapoli

Date: / /2013

(A.G. Mohod)
Chairman,
Advisory Committee and Research Guide

Dr. Y. P. Khandetod
B.Tech. (Agril. Engg.), M. Tech. (P.F.E.), Ph.D. (AGFE)
Professor and Head,
Department of Electrical and Other Energy Sources,
College of Agricultural Engineering and Technology,
Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth,
Dapoli- 415 712, Dist. Ratnagiri,
Maharashtra, India.
.

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Place: CAET, Dapoli

Date: / /2013

(Y. P. Khandetod)
Professor and Head,
Department of Electrical and Other Energy Sources

Prof. dilip MAHALE
B. Tech. (Agril.Engg.), M. Tech. (SWCE)
Associate Dean,
College of Agricultural Engineering and Technology,
Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth,
Dapoli 415 712, Dist. Ratnagiri,
Maharashtra, India.

CERTIFICATE

This is to certify that the thesis entitled **"Development and Evaluation of Biomass Based Composite Water Heater and Dryer"** submitted to the faculty of Agricultural Engineering and Technology, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli, Dist. Ratnagiri, Maharashtra State, in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY (AGRICULTURAL ENGINEERING)** in **RENEWABLE ENERGY SOURCES** embodies the results of ***bonafied*** research work carried out by **Miss Namrata Chintaman Gawali** under guidance and supervision of **Dr. A. G. Mohod,** Associate Professor, Department of Electrical and Other Energy Sources, College of Agricultural Engineering and Technology, Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli and no part of the thesis has been submitted for any other degree, diploma or publication in any other form. She has duly acknowledged all the assistance and help received during the course of investigation.

Place: CAET, Dapoli
Date: / /2013

(dilip MAHALE)
Associate Dean,
College of Agricultural Engineering and Technology

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Place: CAET, Dapoli

Date: **/** **/**2013 **(Namrata Chintaman Gawali)**

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LIST OF ABBREVIATIONS

Abbreviations	**Description**
Agril.	Agricultural
ASTM	American Society for Testing and Materials
BCR	Benefit Cost Ratio
BEE	Bureau of Energy Efficiency
cal	Calorie
cm	Centimeter
C.V.	Calorific Value
Dr. B. S. K. K. V.	Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth
Engg.	Engineering
EOES	Electrical and Other Energy Sources
etc.	Etcetera
et al.	Et. alia (and other)
Fig.	Figure
g	Gram
hr	Hour
hr/kg	Hour per kilogram
i.e.	That is
kcal	Kilo calorie
kcal/kg	Kilo calorie per kilogram
kg	Kilogram
Kg/hr	Kilogram per hour

kg/m^3	Kilogram per cubic meter
m	Meter
m^2	Square meter
m^3	Cubic meter
mg	Milligram
m^3/hr	Cubic meter per hour
min	Minute
MJ/kg	Mega joule per kilogram
mm	Millimetre
MNRE	Ministry of New and Renewable Energy
MS	Mild Steel
m/s	Meter per second
MT	Metric tone
MW	Mega Watt
No.	Number
NPW	Net Present Worth
PBP	Pay Back Period
s	Second
Sr. No.	Serial Number
Vol.	Volume
wb	Wet basis
W	Weight

LIST OF SYMBOL

Symbols	**Description**
@	At the rate
₹	Rupees
π	Pie
Ø	Diameter
ºC	Degree Celsius
º	Degree
%	Percent

ABSTRACT

Development and Evaluation of Biomass Based Composite Water Heater and Dryer

by
Miss. Namrata Chintaman Gawali

College of Agricultural Engineering and Technology
Dr. Balasaheb Sawant Konkan Krishi Vidyapeeth, Dapoli
Dist. Ratnagiri, Maharashtra State (India)
August 2013

Research Guide	**:**	**Dr. A. G. Mohod**
Department	**:**	**Electrical and Other Energy Sources**

Biomass is an important source of energy accounting about one third of the total fuel used in India. Cooking and water heating were major biomass energy operations in rural India. A small boiler (bomb) consumed large biomass fuel for heating water with lower thermal efficiencies. Large amount of heat in term of flue gases were escaped in atmosphere which, needs to be reutilized. The composite biomass based water heater and flue gas based dryer provided the solution for efficient utilization of available biomass for secondary application like drying of product.

The research work was carried out for development and evaluation of biomass based composite water heater and dryer. The performance of the composite unit was carried out to estimate the different operating parameters of water heater (boiler) like quantity of water heated, temperature rise of water, fuel consumption rate, flue gas temperature and thermal efficiency. The quantity of flue gas was estimated using combustion theory and used for design and development of flue gas based dryer. The performance of composite unit was carried out in terms of no load test and full load tests to record various operating parameters. The no load test was carried out at four different combinations of air supply viz. stagnation temperature, partial air flow, free air supply and air velocity (1 m/s) at forced circulation mode. Load testing was

carried out by loading the dryer with onion slices.

The study revealed that the thermal efficiency of water heater without reutilization of flue gases was found to be 26.64 %. Thermal efficiency of water heater were found to be 32.1 %, 31.57 %, 31.95 % and 31.01 %, dryer efficiency were 4.94 %, 6.15 %, 6.78 % and 12.27 % and overall efficiency were 32.76 %, 32.44 %, 32.98 % and 32.48 % at stagnation temperature test, partial air flow test, free air supply test and forced circulation test, respectively. It was observed that, as the flow rate of air increased, the efficiency of the dryer was increased. The obstruction in the passage of flue gases at the outlet increased the efficiency of the water heater. The thermal efficiency of boiler, dryer and overall efficiency were found to be 31.95 %, 23.99 % and 34.99 %, respectively at load test. The thermal efficiency of biomass based water heater was increased by 8.35 % due to reutilization of exit flue gas for drying operation. The temperature of exit flue gas reduced from 333 ºC to 50 ºC, which lead to environmental protection. The economic evaluation of composite unit revealed that, the net present worth (₹), benefit-cost ratio and payback period (months) were found to be ₹ 30461.5 /-, 1.05 and 3.03 months, respectively and revealed its economic feasibility.

I. INTRODUCTION

Biomass is an organic matter of biological origin as a form of stored solar energy which, is captured by the organic matter as it grows. Biomass is an important source of energy accounting for about one third of the total fuel used in India and in about 90% of the rural households. In India, total of about 62-310 Mt of biomass is produced annually (Sudha *et al*., 2003). The current availability of biomass in India is estimated about 120-150 Million MT/annum. Biomass contributes over third of primary energy in India with consumption for fuelwood in domestic sector is 218.5 MT (dry), crop residue is 96 MT and cattle dung cake is 36 MT etc (Shukla,1997). It is estimated that out of total energy consumption, 44% of energy is supplied by non-commercial energy consists of 133 million metric ton of fuel wood, 41 million metric ton of crop waste and 73 million metric ton of animal dung per annum.

Subabul (*Acacia auriculiformis*) is the prominent tree species available in konkan region. Subabul (*Acacia auriculiformis*) occurs near sea level to 400 m, but is most common at elevation less than 80 m. It is predominantly found in the seasonally dry tropical lowlands in the humid and sub-humid zones. It is abundantly available in konkan region and popularly used as the major source of firewood due to its density and high energy content and faster rate of growing (Benth, 2009).

Households in rural areas of developing countries are heavily dependent on wood and other biomass fuels for domestic thermal energy requirements to accomplish the work such as cooking, heating water for bathing and washing of utensils etc. In the rural areas locally manufactured fire wood fuelled metallic water heater called ‘Bomb’ (due to its capsule like shape) is used which is costly, inefficient and pollute the environment. (Babar *et al*. 2009). Biomass fuels are predominantly used in rural households for cooking and water heating as well as by traditional and artisan industries. A small boiler (bomb) consumed large locally available biomass for heating water with lower thermal efficiencies. Large amount of heat in term of flue gases is escaped in atmosphere which needs to be reutilized (Branislav, 2008).

Drying is a technique of preservation for food by reducing the activity of water to a level consistent with the length of desired shelf life and is accompanied by desired biochemical reactions which provide the product with colour, aroma, taste, texture, flavour etc. Drying by artificial heat is more rapid than open air drying and is often necessary in places where humidity is high (Vasanthi *et al*., 2002). Processing of agricultural produce not only contributes to food preservation but also offers better opportunity for expanded product utilization and adds value (Daniel et al., 1996). Open sun drying is time consuming and sometimes it also deteriorates the food material. Different type of dryers such as solar dryer, solar cabinet dryer, solar-biomass hybrid dryer, biomass dryer, etc can be used for efficient drying (Belonio *et al.,* 2012).

The common methods of grain drying in localities today include sun drying and the cabinet grain dryer. These methods have a lot of deficiencies in terms of drying speed, efficiency, productivity, quality and safety (Adzimah *et al.,* 2009). There is need to use different type of dryers which are efficient, required less time and gives the clean products. The biomass fired dryer can give the efficient drying also in the wet season for drying agricultural products in rural areas. The existing biomass based water heaters used in household sector are highly inefficient due to poor combustion design and control. Large quantity of heat is expelled in to atmosphere in the form of flue gases from biomass fired water heater. The heat, which is generated in process by way of fuel combustion or chemical reaction and dumped into the environment even though it could still be reused for some useful and economic purpose (BEE, 2008). The heat available in the flue gas can be reutilized for secondary operation like generation of hot air for drying application.

The composite biomass based water heater and flue gas based dryer will provide the solution for efficient utilization of available biomass. It reutilizes the wastage of flue gas heat for secondary application like drying of product with minimum pollution. The overall efficiency of biomass utilization can be increased by using heat loss into atmosphere.

Keeping in view, the project entitled 'Development and evaluation of biomass based composite water heater and dryer' was under taken with the following objectives-

Objective:

1. To evaluate performance of biomass based water heater.
2. To develop the biomass based composite water heater and dryer.
3. To evaluate the techno-economic performance of developed unit.

II. REVIEW OF LITERATURE

Biomass combustion provides basic energy requirements for cooking and heating. The work carried out internationally and countryside about the development of biomass based composite water heater and dryer is reviewed in order to fulfill the proposed objective. The reviewed literatures were arranged under the following titles.

- Biomass availability
- Household energy consumption
- Drying of Agricultural produce
- Biomass fired drying
- Composite unit

2.1 Biomass availability

Bhattacharya (2001) reported that in the developing countries, biomass fuels were used in a number of commercial applications, e.g. drying/curing/smoking, cooking, baking, pottery etc. There was a great deal of variation in the design of the combustion systems employed in different applications. Energy consumption in the developing countries of Asia was rising rapidly. It was likely that environmental considerations will constrain their access to fossil fuels in the future. As a result, the share of renewable energy in general and biomass in particular, in the total energy supply was expected to rise in the future.

Sudha *et al*., (2003) studied the sustainable biomass production for energy in India and reported that, annually 62-310 Mt of wood would be generated from the surplus land, after all the requirements of biomass, such as domestic fuel wood, industrial wood and sawn wood.

Anonymous (2004) studied the assessment and characterization of biomass in the konkan region and gave the picture about the potential of biomass, availability of decentralized energy option and qualitative analysis of the fuel. Total availability of biomass in Konkan region was estimated to be 91811.9 tons/year.

Ravindranath *et al.*, (2005) reported that in India, fuel wood, crop residues and animal manure were the dominant biomass fuels, which were mostly used in the rural areas, at very low efficiencies. Industrial and municipal (urban) residues such as wastewater, municipal solid wastes (MSW), and crop residues such as rice husk and bagasse could also be used for energy generation. The potential of energy from crop residues, animal manure, MSW, industrial wastewater and biomass fuels that could be conserved for other applications through efficiency improvement was discussed.

Anonymous (2006) reported that the current availability of biomass in India was estimated about 120-150 Million MT/annum. Being an agricultural country and the largest producer of cane sugar, India had abundant quantities of agricultural residues and bagasse.

Anonymous (2008) described the procedure for conversion of proximate analysis of biomass in to ultimate analysis. The mathematical equations for estimation of theoretical air required for combustion, % excess air supplied, actual mass of air supplied and actual mass of dry flue gas were presented based on the elemental composition of biomass.

Benth (2009) revealed that Subabul (*Acacia auriculiformis*) occurs from near sea level to 400 m, but was most common at elevation less than 80 m. It was predominantly found in the seasonally dry tropical lowlands in the humid and sub-humid zones. It was the major source of firewood; its dense wood and high energy contributed to its popularity.

Anonymous (2010) reported that current availability of biomass in India estimated at about 500 million MT per annum. Estimated surplus biomass availability in India was about 120-150 million MT per annum covering agricultural and forestry residues correspond to the potential of about 18,000 MW.

2.2 Household energy consumption

Shukla *et al.*,(1997) reported that biomass contributed over a third of primary energy in India. Biomass fuels was predominantly used in rural households for cooking and water heating as well as by traditional and artisan industries. A recent study estimated demand in India for fuelwood was 201 million tons.

Singh and Patil (2001) developed natural draft gasifier based hot water system having 4-7 kg h^{-1} biomass consumption and aspirated air swirling type producer gas burner. Water holding capacity was 250 litres. For sizing the gasifier a specific gasification rate of 60 kg h^{-1}-m^{-2} and reactor height to diameter ratio 1:1.5. The system revealed that to generate 187 litre of hot water at 80^0C required 65 minutes. The average overall thermal efficiency of the system was 40%.

Anonymous (2008) reported that the market for biomass boilers was estimated to be growing at around 60% per year with several hundred units being installed annually. Biomass boilers offer an alternative to fossil fuelled boilers, in particular oil-fired boilers which were the main option for areas where gas was not available. Biomass boilers produced hot water or steam for process or space heating, or domestic hot water. Biomass room heaters heat spaces and some products could also heat water for wet heating systems or domestic uses.

Branislav *et al.,* (2008) reported that small boilers were used in the household sector for heating water and rooms up to 15 kW. These boilers burned biomass in baled form or another and the products of combustion were discharge into the environment via chimney.

Babar *et al*., (2009) studied the natural draft water heater for rural households. The performance of the stove was also compared with that of the traditional ‘bomb’ water heater. The gasifier heater was observed to be superior in terms of efficiency as well as reduction in emissions. It was also observed that the hot gas temperature remain high and stable over a longer time period in the case of gasifier water heater as compared to the *‘bomb’* water heater.

2.3 Drying of Agricultural produce

Daniel *et al.*, (1996) studied that processing of agricultural produce not only contributed to food preservation but also offered better opportunity for expanded product utilization and added value. Direct sun drying method was time consuming and it was taken 4-6 days to dry agricultural food products (20 mm thick, loading rate 5 kg/m^2) to 14-16 per cent moisture content. Product quality suffered because of prolonged drying, which made the product susceptible to contamination. Solar dryers produced better quality products within a relatively shorter period, but depended mainly on the weather and, therefore, not reliable and attractive during the rainy season or in wet weathers.

Singh and Ramana (1999) designed, fabricated and retrofitted with the Sardar Patel Renewable Energy Research Institute’s solar dryer installed for chilly drying in the field. The biomass consumption of 7-8 kg per hour, an aspirated type producer gas burner and a shell and tube air gas heat exchanger had been coupled with the dryer. For sizing the gasifier, a specific gasification rate of 60 kg h^{-1}-m^{-2}, reactor height to diameter ratio 1:1.5 and generate a 750 m^3 of hot air at an average temperature of 800 ºC.

Vasanthi (2002) studied the development of efficient biomass based dryer for medicinal plants drying. The drying of medicinal plants was conducted at an average air flow rate of 0.2 - 0.3 m/s. When the experiment was carried out with load condition, the maximum temperature of 50 to 55 ºC was attained inside the unit after 30 minutes of combustion process. The maximum temperature of 50- 55 ºC was maintained by adjusting the airflow rate through the door. The efficiency of the biomass fuel based drying system was varied from 30.5% to 37.5% for different selected medicinal plants drying. Dryer efficiency significantly depended on the initial moisture content of the drying material and the airflow rate.

Adzimah *et al.,* (2009) studied that grain drying was very important because it increased the storage life of cereal grains. The common methods of grain drying in our localities today include sun drying and the existing cabinet grain dryer. These methods had a lot of deficiencies in terms of drying speed, efficiency, productivity, quality and safety. The improved design takes care of most of these problems. It was an effective tool for drying and its effectiveness exceeds all forms of drying used locally. The heater supplied the right quantity of heat and incorporated a fan which supplies the right quantity of air needed to distribute this heat evenly to all grains in the drying chamber. This made drying faster and grains were moderately dried.

Seini *et al.,* (2009) reported that the traditional open sun drying of sea cucumber was a long process which takes about two weeks for the product to be dried. The Moto solar dryer designed for the purpose had the advantages of reducing the damages caused to the product by insect, birds, rodents, mirco-organisms and the adverse climatic conditions such as rain, storm etc. The drying time was also reduced considerably. Thus the Moto Solar dryer was an efficient dryer which could enhance the quality of the dried sea cucumber.

2.4 Biomass fired drying

Prasad *et al.,* (2006) reported the performance evaluation of hybrid drier for turmeric (*Curcuma longa L.*) drying at village scale. The developed natural convection solar drier with biomass burner was capable of producing the air temperature between 55 and 60 ^{0}C, that was optimum for dehydration of turmeric rhizomes as well as other spices, herbs, fruits and vegetables. Drying time for turmeric had been drastically reduced compared to open sun drying by 86%. The efficiency of the whole unit observed was 28.57%. The system was predestined for application on small farms in developing countries due to its low investment.

Anon (2009) reported that CAET Dapoli developed copra dryer consumed 120 kg of fuel (coconut husk) to dry a batch of 8 kg coconut halves from initial moisture content 50 % to 6 % final moisture content in 30 hours drying period however, modified CAET copra dryer consumed 20 kg of fuel (coconut husk) to dry 16 kg coconut halves from initial moisture content 50% to 6% final moisture content in 30 hours drying period.

Ehiem *et al*., (2009) studied design and development of an industrial fruit and vegetable dryer**.** A fruit and vegetable–drying device was designed and developed using low price materials that could easily be assessed and maintained by vegetable farmers. The device had a mean thermal efficiency of 82% with average capacity of 258.64 kg/batch. The size, air flow rate and drying time had highly significant effect on gram weight of the tomato slices being dried. For all the tomato sizes and at all air flow rate levels, weight of the tomato decreased with increase in drying time. Also for all the sizes at all drying time levels, weight decreased with increase in air flow rate.

Bello *et al.,* (2010) studied that biomass-furnace dryer had an average thermal efficiency of 59%. This efficiency could be further increased if the heat loss to the environment as conduction and radiation losses through the top cover and outer casing was prevented.

Bastin *et al.*, (1997) reported the water content of several popular raw fruits and vegetables. Fruits and vegetables contain large quantities of water in proportion to their weight. This was important in development of the dryer.

2.5 Composite unit

Anonymous (2008) reported that waste heat was heat, which was generated in process by way of fuel combustion or chemical reaction and then dumped into the environment even though it could still be reused for some useful and economic purpose. Large quantity of hot flue gases was generated from boilers, kilns, ovens and furnaces. If some of this waste heat could be recovered, a considerable amount of primary fuel could be saved. If the exhaust gas heat was suitable for equipment in terms of heat quantity, temperature range, operation time etc, the fuel consumption could be greatly reduced.

Geramitchioski *et al.,* (2011) reported that drying of produce especially vegetables and fruits was one of the oldest forms of food preservation methods known to man. It was the removal of moisture from the product to an optimum level in order to prevent deterioration and preserve their nutritive values. In rural areas, drying was accomplished by direct exposure to the sun because it was relatively easy. The construction of mobile combine solar – biomass dryer for drying of vegetables and fruits with capacity that was suitable for use in single farm and small cooperatives was reported. In this given that apples were dried at temperature of 60-70 ºC to a final moisture content of 20 % with an average drying rate of 8 sunshine hours.

Belonio *et al.,* (2012) reported that simple design of an indirect fired flat bed grain dryer using biomass furnace was developed in 2009 to provide group of farmers, traders, and/or millers a technology that makes drying of grains possible, even during the wet season. The technology used locally available resources and skills making on-site construction possible. The dryer system consisted of biomass furnace which burns biomass (rice husks, corn cobs, etc.) that was available in the farm; an axial fan which moves hot air from the furnace to the drying bin and a drying bin where grains to be dried were held for several hours until the desired level of moisture was reached. The furnace consisted of an inclined grate made of a 10 mm thick mild steel plate which burnt 40 to 60 kg of biomass by direct combustion with excess air.

III. MATERIAL AND METHODS

This chapter deals with the assumption and methodology adopted for development and evaluation of biomass based composite water heater and dryer. The designed system was fabricated and tested at, Department of Electrical and Other Energy Sources, College of Agricultural Engineering and Technology, Dapoli. The study area falls at 17° 45’ N latitude and 73° 26’ E longitude and at an altitude of 256 m above mean sea level. The stepwise methodology to accomplish the research work is summarized under the following sub-headings

1. Characterization of selected biomass
2. Performance evaluation of biomass based water heater
3. Development of biomass based composite water heater and dryer
4. Techno-economic evaluation of biomass based composite water heater and dryer

3.1 Characterization of Biomass fuel (Subabul)

The fuel characterization is very much important to evaluate the performance of system. Subabul (*Acacia auriculiformis*) was used as feed stock for evaluation of water heater and dryer. The selected feed material was characterized in terms of proximate analysis, calorific value and ultimate analysis.

3.1.1 Proximate analysis

The proximate analysis include determination of the moisture content, volatile matter, ash content and fixed carbon of the material on percentage weight basis. The proximate analysis of various constituents of above fuel was carried out as per the standard procedure.

3.1.1.1 Moisture content

As per ASTM D-3173, the moisture content of raw biomass was determined by calculating the loss in weight of material using hot air oven drying method. About 1 g of finely powdered air-dried sample was weighed in crucible. The crucible was placed in an electric hot air-oven maintained at 104 ºC. The crucible was allowed to remain in oven till constant weight was obtained and then taken out (with the help of a pair of tongs), cooled in desiccators and weighed. Loss in weight was reported as moisture on percentage-basis.

$$\text{Moisture content (\% wb)} = \frac{W_2 - W_3}{W_2 - W_1} \times 100 \quad \ldots (3.1)$$

Where,
W_1 = Weight of crucible, g
W_2 = Weight of crucible + sample, g
W_3= Weight of crucible + sample, after drying, g

3.1.1.2 Volatile matter

As per ASTM D–3175, volatile matter was determined by keeping the dried sample obtained after moisture content determination in a closed crucible at 950ºC for six minutes in a muffle furnace. The crucible was cooled first in air, and then in desiccators and weighed again. The loss in weight was taken as the volatile matter present in the sample on percentage basis.

$$V.M.(\%) = \frac{W_3 - W_4}{W_2 - W_1} \times 100 \quad \ldots (3.2)$$

Where,

w_1 = weight of crucible, g

w_2 = weight of crucible + sample, g

w_3 = weight of crucible + weight of oven dried sample, g

w_4 = weight of crucible + weight of sample after heating in muffle furnace, g

3.1.1.3 Ash content

As per ASTM D-3174, the residual samples obtained after volatile matter determination was heated gradually in a muffle furnace at 750 ºC for two hours. The crucible was taken out, cooled first in air, then in desiccator and weighed. Heating, cooling and weighing was repeated till constant weight was recorded. The weight of residue was represented as the ash content of the sample on percentage basis.

$$A.C.(\%) = \frac{W_5 - W_1}{W_2 - W_1} \times 100$$

…(3.3)

Where,

w_1 = weight of crucible, g

w_2 = weight of crucible + weight of oven dried sample, g

w_5 = weight of crucible + weight of sample after heating in muffle furnace, g

3.1.1.4 Fixed carbon

The fixed carbon on percentage basis is calculated by subtracting the sum of percentage of moisture content, volatile matter and ash content from 100.

Fixed carbon (%) = 100 – % of (moisture content + volatile matter + ash)

...(3.4)

3.1.2 Calorific value of biomass

The higher heating value of subabul (*Accacia auriculiformis*) was determined using of bomb calorimeter (ASTME-711), where the combustion was carried out in environment with high pressure of oxygen to ensure complete combustion. The higher calorific value of solid fuel using the bomb calorimeter experiment was determined as

$$\text{Calorific value (kcal/kg)} = \frac{[(W+w)\times(T_2-T_1)]-E_1}{X}$$ …

(3.5)

Where,

W = Mass of water placed in the calorimeter (g),

w = Water equivalent of the apparatus (g),

T_1 = Initial temperature of water in the calorimeter (˚C),

T_2 = Final temperature of water in the calorimeter (˚C),

X = Mass of fuel sample taken in the crucible (g)

E_1 = Correction for heat of combustion of firing wire and cotton thread (cal).

3.1.3 Ultimate analysis

Carbon, hydrogen, oxygen and nitrogen content of the fuel were determined under the ultimate analysis. Using the values of proximate analysis, ultimate analysis of the fuels was calculated theoretically by using the various formulas (Bureau of Energy Efficiency, 2008).

3.1.3.1 Carbon content

Carbon content of the sample was calculated as,

$$C = 0.97\ FC + 0.7\ (VM - 0.1\ A) - M\ (0.6 - 0.01\ M),\ \% \quad ...(3.6)$$

3.1.3.2 Hydrogen content

Hydrogen content of the sample was calculated as,

$$H = 0.036\ FC + 0.086\ (VM - 0.1\ A) - 0.0035\ M^2\ (1 - 0.02M),\ \% \quad ...(3.7)$$

3.1.3.3 Nitrogen content

Nitrogen content of the sample was calculated as,

$$N_2 = 2.10 - 0.020\ VM,\ \% \quad ...(3.8)$$

3.1.3.4 Oxygen content

Oxygen content of the sample was calculated by difference as,

$$O_2 = 100 - \%\ \text{of}\ (C + H + N + Ash),\ \% \quad ....(3.9)$$

Where,
FC = Fixed carbon, %
A = Ash, %
VM = Volatile matter, %
M = Moisture content, %

3.2 Performance evaluation of biomass based water heater

The performance evaluation of biomass based water heater was carried out to estimate the energy requirement for water heating at domestic level. The performance of biomass based water heater was studied by conducting 3 test runs using Subabul (*Acacia Auriculiformis*) as a fuel. The technical specifications of the shell and tube type water heater are depicted in Table 3.1. The pictorial view of biomass water heater is shown in Plate 3.1. The schematic of biomass water heater is shown in Fig. 3.1.

The following parameters were recorded during the performance evaluation of biomass based water heater using Subabul (*Acacia auriculiformis*) as fuel.

3.2.1 Quantity of water heated, lit

The quantity of heated water was measured by using measuring cylinder. The water heater was filled with fresh water to its full capacity (27 lit) during each test run.

3.2.2 Initial and final temperature of water, ºC

Initial and final temperature of water was measured by glass thermometer and flame thermometer respectively. Temperature was measured at 10 minute interval during the test.

Table 3.1 Technical specifications of water heater (Boiler)

Sr. No.	Particulars	Specifications
1.	Total height of the boiler, m	1.0
2.	Height of the boiler shell, m	0.61
3.	Height of the combustion chamber, m	0.16
4.	Height of the ash chamber, m	0.12
5.	Height of the boiler outlet, m	0.11
6.	Diameter of the boiler outlet, m	0.09
7.	Diameter of the boiler shell, m	0.25
8	Diameter of the combustion chamber & ash chamber, m	0.15
9.	Height of the water inlet pipe, m	0.65
10.	Diameter of the water inlet pipe, m	0.025
11.	Diameter of the water outlet pipe, m	0.02
12.	Water holding capacity, lit	27
13.	Operating temperature of water, ºC	60

3.2.3 Operating time, hr

Time required to attend the temperature of boiler from ambient temperature to 60 ºC was treated as the operating time of boiler/batch. It was measured with the help of stop watch.

3.2.4 Fuel consumption rate, kg hr^{-1}

Fuel consumption rate is the amount of fuel required to heat the water to 60 ºC in given time. It was measured with the help of weighing balance.

3.2.5 Thermal efficiency, %

Thermal efficiency of boiler is the ratio of energy required to heat the water to the energy supplied to the boiler (BEE-2008). Using direct method, it was computed as,

$$\eta_{boiler} = \frac{m \times C_{pw} \times \Delta T}{mf \times HCV}$$

...(3.10)

Where,

m- Mass of water, kg

c_{pw}- Specific heat of water, kcal/ kg ºC

ΔT- Change in temperature = $T_2 - T_1$

T_1- Initial temperature of water, ºC

T_2- Final temperature of water, ºC

m_f – Mass of fuel used, kg

HCV- Higher calorific value of fuel, kcal/kg

3.2.6 Flue gas temperature, ºC

The temperature of flue gases which liberated from boiler outlet was measured by using K-type thermometer at an interval of 10 minutes during each test (Plate 3.2).

3.3 Development of biomass based composite water heater and dryer

The development of biomass based composite water heater and dryer was carried out based on performance of biomass based water heater system. The quantity of fuel burnt in operating time, type of fuel, efficiency of water heater, flue gas temperature and quantity of flue gas were considered while developing the biomass based composite water heater and dryer.

3.3.1 Heat available in flue gas, kcal/kg of fuel

The heat available in the flue gases liberated from the boiler was estimated by considering the proximate and computed ultimate analysis of fuel, as per BEE-2008 procedure. The average performance of biomass water heater was considered to estimate the fuel consumption rate and batch operating time. The actual mass of flue gas liberated during the batch was estimated in term of kg of flue gas per kg of fuel using combustion theory and elemental analysis. The quantity of flue gas in term of cubic meter of flue gas per kg of fuel (m^3/kg) was estimated by considering the volume of exhaust gas and air required (stoichiometric + excess air) for combustion.

The heat available in the flue gas in terms of kcal/kg of fuel was estimated using the mass of flue gases, specific heat and average temperature of flue gas liberated in the atmosphere. The sample calculations for estimation of heat in flue gas are summarized in appendix D.

3.3.2 Design of flue gas based dryer

The following equations were considered while developing and evaluating the biomass based composite water heater and dryer system.

1. Mass of water to be removed during drying, kg

$$M_w = \frac{m_i - m_f}{1 - m_f} \times W \quad \text{...(3.11)}$$

Where,
M_w= Mass of water removed, kg
m_f = Final moisture content, %
m_i = Initial moisture content, %
W = Weight of product, kg.

2. Volumetric flow rate of air, m^3 / hr

$$Q_a = \frac{M_w}{\rho a (Hf - Hi)} \quad \text{...(3.12)}$$

Where,
M_w= Mass of water removed, kg
ρa = Density of air, kg/m^3
H_f= Final humidity ratio, kg/kg
H_i= Initial humidity ratio, kg/kg

3. Volume of air to effective drying, m^3

$$(Va) = \frac{Qa}{\rho a} \quad ...(3.13)$$

Where,

ρa is density of air in kg/m^3

4. Quantity of heat required to effect drying, kcal

$$Q = \left(W.C_{pp}.\Delta T\right) + \left(M_w.C_{pw}.\Delta T\right) + \left(M_w.\lambda\right) \quad ...(3.14)$$

Where,

W = Weight of product, kg

C_{pw} = Specific heat of water, kcal /kg ^oC

C_{ck} = Specific heat of product, kcal /kg ^oC

T_d = Drying temperature, ^oC

T_a = Ambient temperature, ^oC

M_w = Mass of water to be removed, kg

λ = Latent heat of vaporization, kcal/kg

The biomass based composite unit was fabricated using locally available material. The flue gas based drying unit consists of following components,

i. **Drying chamber:**

Drying chamber of the composite water heater and dryser was made up of GI sheet (16 SWG). It consist of outer body and inner body with the dimensions of 550 mm × 550 mm × 350 mm and 500 mm × 500 mm × 300 mm respectively. The inner passage of 25 mm from each side was used as passage for hot flue gases.

ii. **Heat exchanger:**

The flue gases from the water heater were passed through the 1200 mm long square GI duct (100 mm × 100 mm) made up of GI material (16 SWG) to the flue gas passage of drying chamber. A 1200 mm long circular MS pipe (50 mm Ø) was placed inside the duct to absorb the heat from flue gases and passed into the drying chamber.

iii. **Outlet chimneys:**

The flue gas exit chimney (25 mm Ø) and moist air exit chimney (25 mm Ø) installed to drying chamber to expel the flue gases and moist air respectively.

iv. **Drying tray:**

Two drying trays (500mm × 500mm) made up of MS wire mesh, were placed 100 mm apart inside the drying chamber.

v. **Opening door:**

An opening door (300mm × 250mm) was provided to the drying chamber with the handle.

vi. **Stand:**

Stand of the composite unit was made up of MS angle (Height- 1100 mm) to support the drying chamber.

Technical specifications of dryer are depicted in Table 3.2. The schematic view of composite unit of water heater and dryer is shown in Fig. 3.2. The pictorial view of composite unit is shown in Plate 3.2.

Table 3.2 Technical specifications of Dryer

Sr. No.	Particulars	Specifications, mm	Material
1.	Drying chamber Inner box Outer box	 500×500×300 550×550×350	GI sheet 18 SWG 16 SWG
2.	Heat exchanger Square duct Circular pipe	 1200 × 100 × 100 50 mm Ø	 GI 16 SWG MS
3.	Outlet chimneys Flue gas exit Moist air exit	 25 mm Ø 25 mm Ø	 GI pipe
4.	Drying trays (2 Nos.)	500×500	MS wire mesh
5.	Opening door	300 × 250	GI 16 SWG
6.	Stand	Height- 1100	MS angle

3.3.3 Cost of composite unit:

The cost of biomass water heater was ₹6000 /- and the fabrication cost of flue gas based dryer was computed as ₹ 9500 /- includes labor and installation charges. The overall cost of composite unit was ₹ 15500 /- (Appendix F).

3.4 Techno-economic evaluation of biomass based composite unit for water heater and dryer

The performance evaluation of newly developed flue gas based dryer coupled with the biomass based water heater was carried out by conducting three trial test runs using subabul (*Acacia auriculiformis*) as a fuel. The performance of composite unit was carried out in terms of,

1. No load test
2. Load test

3.4.1 No load test

The performance testing of composite unit was carried out without loading the dryer with product to record the different parameters of water heater viz; quantity of water heated, temperature rise, fuel consumption rate, operating time etc as described in section 3.2 along with the operating parameter of flue gas based dryer as follows

i. Inlet flue gas temperature, T_{fg1}, °C

The temperature of flue gases liberated from boiler outlet was measured by flame thermometer at an interval of 5 minute during test run.

ii. Temperature of exit flue gas, T_{fg2}, °C

Temperature of the exit flue gases was measured at the outlet of the drying chamber with the help of k-type thermometer with data logger at an interval of 5 minute during test run.

iii. Ambient air temperature, T_{amb}, °C

Ambient temperature was measured at the atmosphere before entering in to the heat exchanger pipe with the help of glass thermometer at an interval of 5 minute.

iv. Inlet air temperature, T_i, °C

The inlet air entering the drying chamber after heat exchanger was measured with the help of k-type thermometer with data logger at an interval of 5 min.

v. Temperature on 1st tray, T_{t1}, °C

The temperature of air over the 1st tray was measured with the help of k-type thermometer with data logger at an interval of 5 minute.

vi. Temperature on 2nd tray, T_{t2}, °C

The temperature of air over the 2nd tray was measured with the help of k-type thermometer with data logger at an interval of 5 minute.

vii. Exit air temperature, T_{ex}, °C

Temperature of exit air was measured at outlet of dryer with the help of k-type thermometer with data logger at an interval of 5 minute (Fig. 3.3).

The performance evaluation of composite unit on no load condition was carried out by conducting the test runs with following operating condition,

i. Stagnation temperature

The inlet and outlet of air was closed throughout the test runs.

ii. Partial air flow (Natural convection)

The inlet and outlet of air supply were partially opened (50 %) during the test and air was circulated by natural convection.

iii. Free air supply (Natural convection)

The inlet and outlet of air supply were fully opened and air was circulated by natural convection.

iv. Forced circulation mode

The inlet and outlet of air supply was fully opened and air circulation was carried out using D.C. fan provided at one end of air supply system (1 m/s velocity).

3.4.1.1 Thermal analysis of composite unit at No load

Thermal analysis of the composite unit was estimated in terms of water heating efficiency, drying efficiency and overall efficiency as,

i. Thermal efficiency of water heating

Thermal efficiency of boiler is the ratio of and it was measured by following equation,

$$\eta_{boiler} = \frac{m \times C_{pw} \times \Delta T}{mf \times HCV} \quad ...(3.15)$$

Where,

m = mass of water, lit

c_{pw}= Specific heat of water, Kcal/ kg ^{0}C

$\Delta T = (T_2 - T_1)$

T_1= Initial temperature of water, ^{0}C

T_2= Final temperature of water, ^{0}C

m_f – Mass of fuel used, kg

HCV- Higher calorific value of fuel, Kcal/kg

ii. Drying efficiency

$$\eta_{dryer} = \frac{(m_a \times C_{pa} \times \Delta T1)}{(m_{fg} \times C_{pfg} \times \Delta T2)}$$

...(3.16)

Where,

m_a- mass of air, kg

m_{fg}- mass of flue gas, kg

C_{pa}- specific heat of air, Kcal/kg ^{0}C

C_{fg}- specific heat of flue gas, Kcal/kg ^{0}C

ΔT_1-Temperature difference in inlet and outlet drying air, ^{0}C

ΔT_2- Temperature difference in hot flue gas and exit flue gas temperature, ^{0}C

iii. Overall efficiency

$$\eta_{overall} = \frac{(m \times C_{pw} \times \Delta T) + (m_a \times C_{pa} \times \Delta T1)}{m_f \times HCV}$$

...(3.17)

Where,

m_f = mass of fuel, kg

HCV = Higher calorific value of fuel, Kcal/kg

3.4.2 Load test of composite unit

Load test of composite unit was carried out to dry the product. Composite unit was tested on forced circulation mode with loading of onion slices. The initial moisture content of onion slices was determined using oven drying method before loading in the dryer. The weight reduction of product was measured at an interval of 30 minute with the help of weighing balance. The drying test run was conducted for 4 hours and moisture evaporated was estimated (Plate 3.4).

The thermal profile of composite unit at load test was recorded for air temperature, flue gas temperature and temperature inside the dryer same as described in no load test.

3.4.2.1 Thermal analysis at load test

Thermal analysis of composite unit on load test was estimated in term of drying efficiency and overall efficiency of the composite unit by considering the latent heat of vaporization of water and sensible heat as described in no load testing.

i. Drying efficiency

$$\eta_{dryer} = \frac{(m_w \times C_{pw} \times \Delta T1) + (m_w \lambda)}{(m_{fg} \times C_{pfg} \times \Delta T2)}$$

...(3.18)

Where,

m_w= mass of water evaporated, kg

m_{fg}= mass of flue gas, kg

m_w= moisture evaporated, kg

C_{pa}= specific heat of air, Kcal/kg ^{0}C

C_{pfg}= specific heat of flue gas, Kcal/kg ^{0}C

ΔT_1=Temperature difference in ambient temperature and product temperature, ^{0}C

ΔT_2=Temperature difference in hot flue gas and exit flue gas, ^{0}C

λ – Latent heat of vaporization, kcal/kg

ii. **Overall efficiency**

$$\eta_{overall} = \frac{(m \times C_{pw} \times \Delta T) + (m_w \times C_{pw} \times \Delta T1) + (m_w \lambda)}{m_f \times HCV}$$

...(3.19)

3.4.3 Economic evaluation

The economic evaluation of the developed biomass based composite water heater and dryer were carried out by considering the fuel saving over the existing system and cost incurred in development of system. The economics of the system were carried out in terms of,

1. Net present value
2. Benefit-cost ratio
3. Payback period (years)

i. Net present worth (NPW)

The difference between the present value of all future returns and the present money required to make an investment is the net present worth or net present principals for the investment. The present value of future returns can be calculated through the use of discounting. The interest rate was assumed to be discount rate for discounting purpose.

The mathematical statement for net present worth can be written as

$$\text{Net Present Worth} = \sum_{t=1}^{t=n} \frac{B_t - C_t}{(1+i)^t}$$

...(3.20)

Where,

C_t = Cost in each year

B_t = Benefit in each year

t = 1, 2, 3................n

i = Discount rate

ii. Benefit cost ratio (BCR)

This ratio was obtained when the present worth of the benefit stream was divided by the present worth of the cost stream. The formal selection criterion for the benefit-cost ratio for measure of project worth was to accept projects for a benefit-cost ratio of one or greater.

The mathematical benefit-cost ratio can be expressed as

$$\text{Benefit Cost Ratio} = \frac{\sum_{t=1}^{t=n} \frac{B_t}{(1+i)^t}}{\sum_{t=1}^{t=n} \frac{C_t}{(1+i)^t}}$$

...(3.21)

Where,

C_t = Cost in each year

B_t = Benefit in each year

t = 1, 2, 3................n

i = Discount rate, %

iii. Pay-back period

The payback period is the length of time from the beginning of the project until the net value of the incremental production stream reaches the total amount of the capital investment. It shows the length of time between cumulative net cash outflow recovered in the form of yearly net cash inflows.

3.5 Instruments used during study

Following instruments/equipments were used during the evaluation of the water heater and dryer (Table 3.3). The pictorial view of different instruments is shown in plate 3.5.

Table 3.3 Instruments used during study

Sr. No.	Name of Instrument	Specification	Measurement
1.	Digital thermometer	Make-MECO-990 K Thermometer (Chromel-Alumel) Range: -200 to 1370 ºC, Accuracy: ±2% L.C. = 0.001	Temperature
2.	Bomb calorimeter	Make: Parr, Oxygen bomb calorimeter (1341) as per ASTM-D271-70 Energy Equivalent: 2426 calories/ ºC Range:3000-10000 cal g-1	Calorific value
3.	Weighing balance	Make: PHONIX Capacity : 30 kg, Accuracy: 2 g	Measurement of weight
4.	Data logger	8 Channel Temperature range: 0-100 ºC, Accuracy: ± 2% L.C. = 0.001	Measurement of temperature
5.	Digital stopwatch	Make: Lutron, Accuracy: 1/10 sec	Time measurement
6.	Oven	Make: Quality QE-102 Temperature range: 50 – 350 ºC	Proximate analysis
7.	Muffle furnace	Make: Quality NSW-101, MF-1 Temperature range: 0 – 1200 ºC Rating: 1.6 kW	
8.	Glass thermometer	Temperature range: 0 – 50 ºC L.C. = 0.1	Temperature
9.	Measuring cylinder	2000 ml	Quantity of water
10.	Digital anemometer	Make: LUTRON Measurement = m/s, km/h, ft/min, Operating temp. = 0 ºC to 50 ºC Operating humidity = < 80 % RH	Air flow rate

IV. RESULTS AND DISCUSSION

This chapter deals with the results obtained from the study undertaken with the objectives to evaluate the performance of biomass based water heater, development of biomass based composite water heater and dryer and evaluation of the economic performance of newly developed composite unit. The newly developed composite unit was fabricated and tested at Department of Electrical and Other Energy Sources, CAET, DBSKKV, Dapoli (17°45’ N and 73°26’ E). The performance of biomass based water heater was evaluated in terms of operating time, fuel consumption rate, temperature of flue gas, volume of flue gas and thermal efficiency of water heater. The development and performance of composite unit was evaluated in terms of temperature of exit flue gas, inlet and outlet air temperature, load and no load testing, temperature profile of drying chamber, efficiency of dryer and overall efficiency. Further the economic analysis of the system was evaluated in terms of net present worth, benefit-cost ratio and payback period.

4.1 Characteristics of biomass, Subabul (*Acacia auriculiformis*) feed stock

The characteristic of selected biomass was carried out in term of proximate analysis, calorific value and ultimate analysis of fuel.

4.1.1 Proximate analysis

The air dried biomass of Subabul (*Acacia auriculiformis*) cut into convenient size to use as feed stock for testing of composite unit was evaluated for physical and thermal properties. The physical properties include moisture content, volatile matter, ash content and fixed carbon were determined by using three sample of biomass (Appendix A). The results obtained from proximate analysis are depicted in Table 4.1.

Table 4.1 Proximate analysis of biomass Subabul (*Acacia auriculiformis*)

Sr. No.	Property	Values
1.	Moisture content,%	7.05
2.	Volatile matter,%	69.65
3.	Ash content,%	2.03
4.	Fixed carbon,%	21.26

The proximate analysis of the selected biomass, Subabul (A*cacia auriculiformis*) revealed that it was suitable for combustion. It was observed that, the average moisture content of biomass was found to be 7.05 per cent, which is within the acceptable limit for better combustion (< 15 %). The volatile matter content was found to be 69.65 per cent. The ash content of the biomass was found to be 2.03 per cent under study. The lower amount of the ash content in the fuel under study revealed their suitability for the combustion with minimum blocking of flow of air and fuel. The most desirable component, which governed the suitability of the fuel for combustion, that the fixed carbon was found to be 21.26 per cent in Subabul *(Acacia auriculiformis)*. The higher heating value of biomass was found to be 3040 Kcal/kg which revealed it suitability for combustion to produce the heat.

4.1.2 Ultimate analysis

The ultimate analysis of biomass Subabul (*Acacia auriculiformis*) was estimated in order to determine the carbon, hydrogen, nitrogen and oxygen percentage. Ultimate analysis of the given sample was estimated theoretically from the results obtained in proximate analysis (Appendix B). The results obtained from the ultimate analysis of the feed stocks are shown in Table 4.2.

Table 4.2 Ultimate analysis of biomass Subabul (*Acacia auriculiformis)*

Sr. No.	Property	Values
1.	Carbon content,%	65.49
2.	Hydrogen content,%	6.58
3.	Nitrogen content,%	0.70
4.	Oxygen content,%	27.20

It was observed that, the Carbon (65.49 %) and Hydrogen (6.58 %) content of selected biomass indicated its suitability as wood fuel for combustion. The lower Nitrogen content (0.7 %) indicated the liberation of low inert gases during combustion. The higher Oxygen (27.20 %) revealed the suitability for proper combustion process.

4.2 Performance evaluation of biomass based water heater

The performance of the biomass based water heater was carried out using selected biomass feed stock i.e. Subabul (*Acacia auriculiformis)* (Appendix-C). The results obtained from the testing of water heater are summarized in Table 4.3. It was observed that the average initial and final temperature of the water was found as 28 ºC and 61 ºC respectively. The average operating time of the boiler to raise the temperature from 28 ºC to 61 ºC was found to be 35 min. The average fuel consumption of the boiler to raise the temperature from initial (28 ºC) to final (61 ºC) was found to be 1.10 kg. The average fuel consumption rate of the boiler was 1.89 kg/hr.

Table 4.3 Operating parameters of biomass based water heater

Sr. No.	Parameters	Value
	Quantity of water heated	27 lit
	Initial temperature of water	28 ºC
	Final temperature of water	61 ºC
	Operating time	35 min
	Fuel consumption	1.10
	Fuel consumption rate	1.89 kg/hr
	Heat available in flue gas	1515.5 kcal/hr
	Volume of flue gas	32.26 m^3 /hr
	Mass of flue gas	20.50 kg/hr
	Thermal efficiency (Hourly basis)	26.64 %
	Flue gas temperature	333 ºC

The heat available in the flue gases liberated from the boiler was estimated by considering the proximate and computed ultimate analysis of fuel (Appendix-D). The heat available in flue gas was found to be 1515.5 kcal/hr. The volume of flue gas and mass of flue gas was estimated as 32.26 m^3/hr and 20.50 kg/hr respectively. The average thermal efficiency of the boiler was found to be 26.64 %. Temperature of the flue gas was measured at an interval of 10 min and was found to be 333 ºC. From the performance testing it was revealed that, large amount of heat (1515.5 kcal/hr) was liberated in atmosphere with temperature in the tune of 300 ºC. This heat losses needs to reutilized for additional work.

4.3 Performance evaluation of composite water heater and dryer

The flue gas based dryer was developed and coupled with biomass heater. The performance of composite water heater and dryer was evaluated to determine the various operational parameters. The performance of the composite unit was analyzed under following headings.

- No load testing
- Load testing

4.3.1 No load testing of composite unit

No load testing of drying chamber was conducted by series of test runs by considering four combinations of air supply. The temperature at various locations was measured at an interval of 5 minutes starting from the ignition of the fuel to the end of the test run.

4.3.1.1 Stagnation temperature test

The inlet and outlet of the air supply was fully closed during the test run. The operating parameters recorded during the test are summarized in Appendix-G-1.

a. Variation of flue gas temperature

The temperature of the flue gas was measured from starting of the test to the end of the test of composite unit. The variation of flue gas temperature with respect to operating time is shown in Fig 4.1.

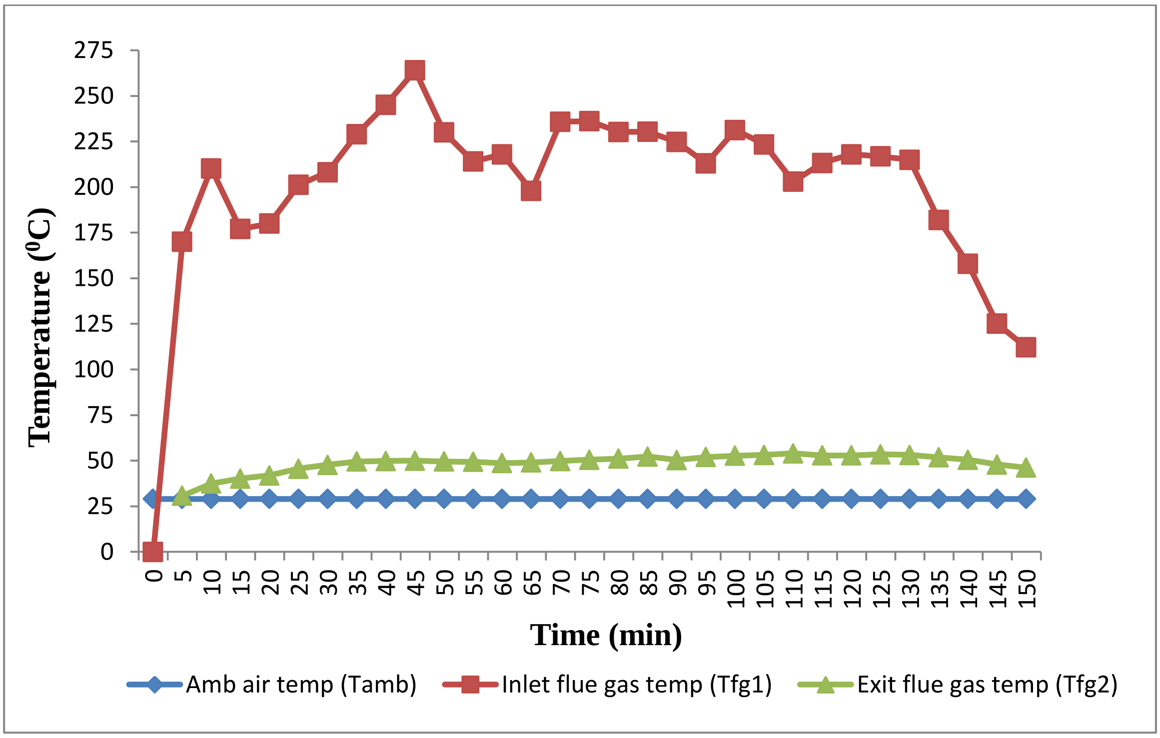

Fig. 4.1 Variation of flue gas temperature (stagnation temperature) at no load

It was observed that, the average flue gas temperature (T_{fg1}) at outlet of water heater was found to be 207.08 ºC. The average flue gas temperature (T_{fg2}) at outlet of flue gas at exit chimney was found to be 48.80 ºC. The mass of flue gas liberated from the water heater was estimated to be 50.9 kg. The average temperature absorb in the drying system was about 158.28 ºC, which was used to generate the hot air for drying application. The significant variation in inlet flue gas temperature may be due to poor controlled combustion process at combustion chamber. The exit flue gas temperature was observed to be constant due to proper flue gas channelling and retention of heat in drying system.

b. Variation of air temperature

The temperature of the air was recorded at different locations of the composite unit during stagnation temperature test. The air temperature at inlet of drying chamber (T_i), temperature above the 1st tray (T_{t1}), temperature above the 2nd tray (T_{t2}) and temperature at exit chimney (T_{ex}) was measured and variation is shown in Fig 4.2.

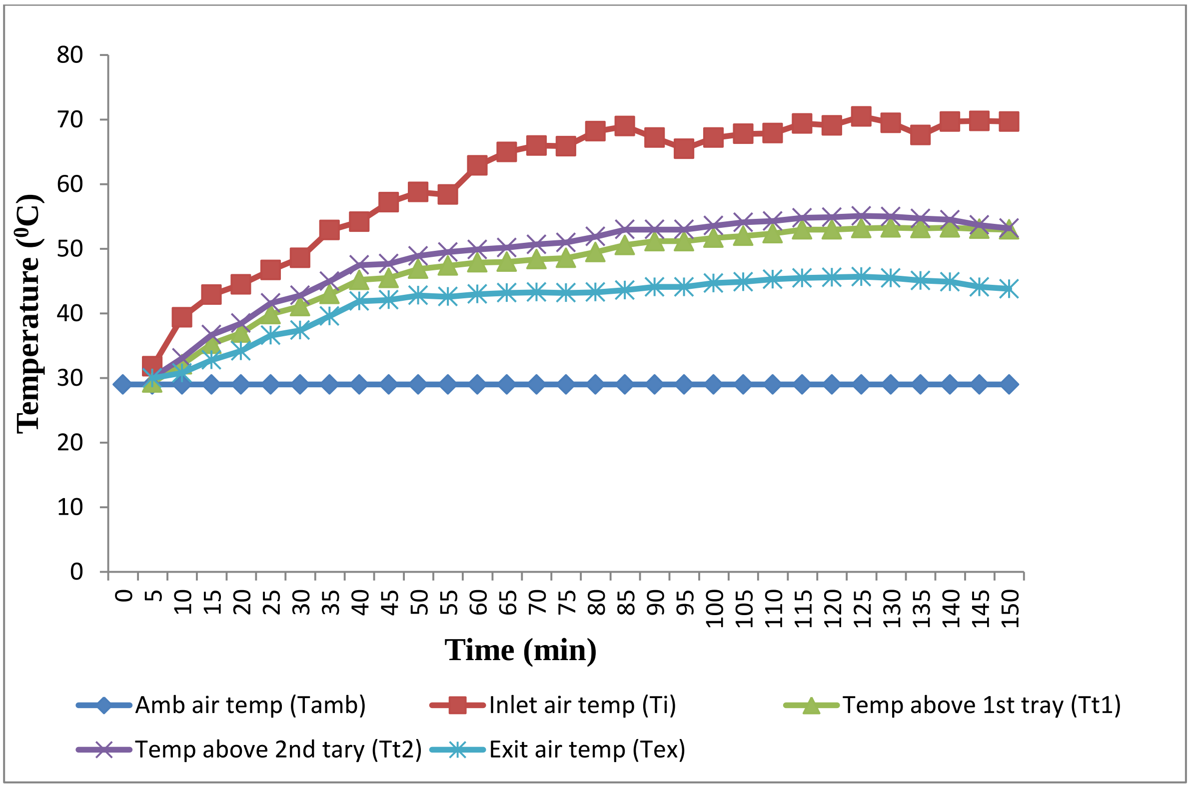

Fig.4.2 Variation of air temperature (stagnation temperature) at no load

It was observed that the average inlet air temperature (T_i) was found to be 60.77 ºC. The average temperature over the 1st tray (T_{t1}) was fond to be 47.31 ºC. The average temperature over 2nd tray (T_{t2}) was fond to be 49.06 ºC. The average exit air temperature (T_{ex}) was fond to be 41.79 ºC. The suitable air temperature (above 45 ºC) for drying of agriculture products was achieved after 25 minutes of operation and remains constant throughout the test run. The mass of air heated during the test was estimated to be 12.07 kg with average temperature rise of 20 ºC over ambient.

The mass of fuel burnt, water heated, operating time, mass of flue gas and mass of air during the test run and average temperature at different location were used to estimate the different efficiencies of the composite system. The average thermal efficiency of water heater during stagnation temperature test was found to be 32.1 %. The average drying efficiency of flue gas based dryer during no load test at stagnation temperature condition was found to be 4.94 %. The overall efficiency of composite unit on no load at stagnation temperature condition was estimated as 32.76 %.

The increase in efficiency of composite unit (4.94 %) over thermal efficiency of water heater (32.1 %) revealed the advantage of reutilization of flue gases for drying application with liberation of cold flue gases (48.8 ^{0}C) into atmosphere as compared to 300 ^{0}C during single unit for water heating.

4.3.1.2 Partial air flow test

The inlet and outlet of the air supply was partially closed (50 %) during the test run. The operating parameters recorded during the test are summarized in Appendix-G-2.

a. Variation of flue gas temperature

The temperature of the flue gas was measured from starting of the test to the end of the test of composite unit. The variation of flue gas temperature with respect to operating time is shown in Fig 4.3.

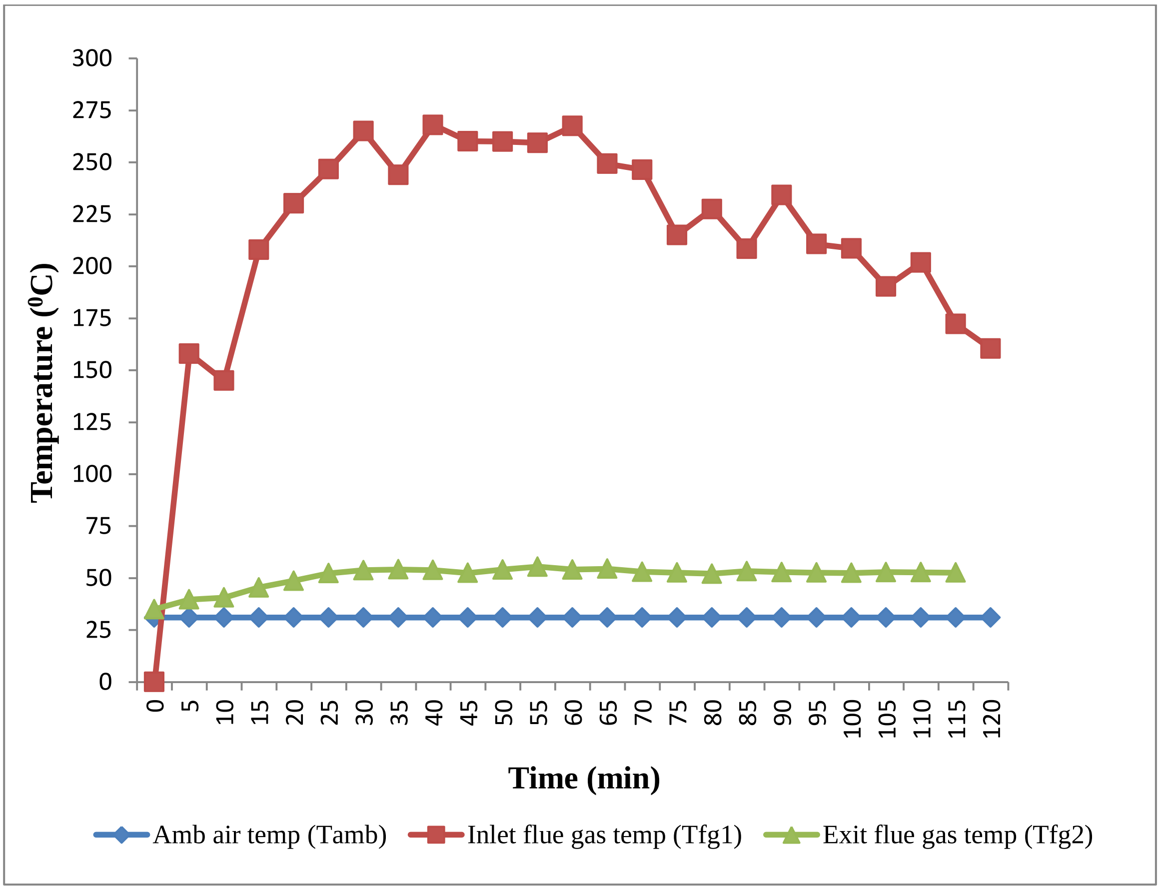

Fig.4.3 Variation of flue gas temperature (partial air flow test) at no load

It was observed that, the average flue gas temperature (T_{fg1}) at outlet of water heater was found to be 222.36 ºC. The average flue gas temperature (T_{fg2}) at outlet of flue gas at exit chimney was found to be 50.90 ºC. The mass of flue gas liberated from the water heater was estimated to be 40.97 kg. The average temperature absorb in the drying system was about 171.46 ºC, which was used to generate the hot air for drying application. The exit flue gas temperature was observed to be constant due to proper flue gas channelling and retention of heat in drying system.

b. Variation of air temperature

The temperature of the air was recorded at different locations of the composite unit during partial air flow test. The air temperature at inlet of drying chamber (T_i), temperature above the 1st tray (T_{t1}), temperature above the 2nd tray (T_{t2}) and temperature at exit chimney (T_{ex}) was measured and variation is shown in Fig 4.4.

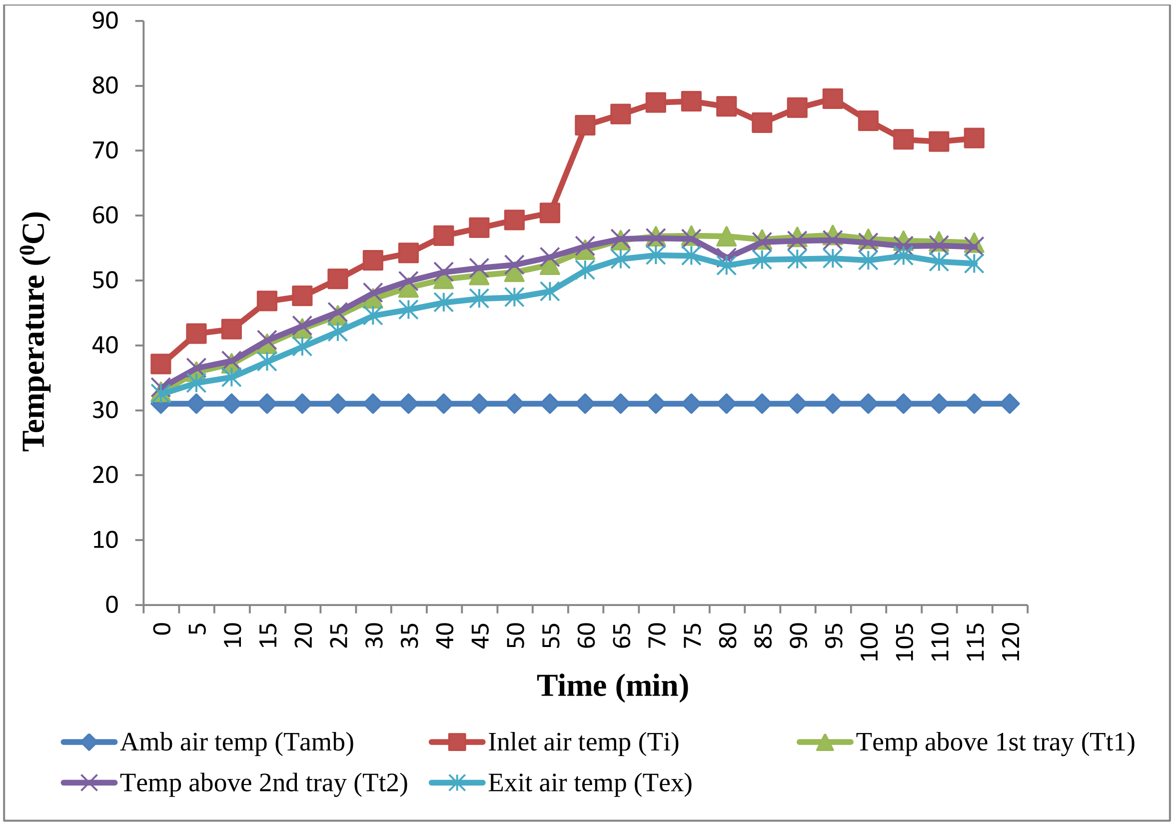

Fig.4.4 Variation of air temperature (partial air flow test) at no load

It was observed that the average inlet air temperature (T_i) was found to be 62.82 ºC. The average temperature over the 1st tray (T_{t1}) was found to be 50.40 ºC. The average temperature over 2nd tray (T_{t2}) was found to be 50.48 ºC. The average exit air temperature (T_{ex}) was fond to be 47.41 ºC. The suitable air temperature (above 45 ºC) for drying of agriculture products was achieved after 20 minutes of operation and remains constant throughout the test run. The mass of air heated during the test was estimated to be 12.98 kg with average temperature rise of 22 ºC over ambient.

The average thermal efficiency of water heater during partial air flow test was found to be 31.57 %. The average drying efficiency of flue gas based dryer during no load test at partial air flow condition was found to be 6.15 %. The overall efficiency of composite unit on no load at partial air flow condition was estimated as 32.44 %.

The increase in efficiency of composite unit (6.15 %) over thermal efficiency of water heater (31.57 %) revealed the advantage of reutilization of flue gases for drying application with liberation of cold flue gases (50.90 ºC) into atmosphere as compared to 300 ºC during single unit for water heating.

4.3.1.3 Free air supply test

The inlet and outlet of the air supply was fully opened (Naturally) during the test run. The operating parameters recorded during the test are summarized in Appendix-G-3.

a. Variation of flue gas temperature

The temperature of the flue gas was measured from starting of the test to the end of the test of composite unit. The variation of flue gas temperature with respect to operating time is shown in Fig 4.5.

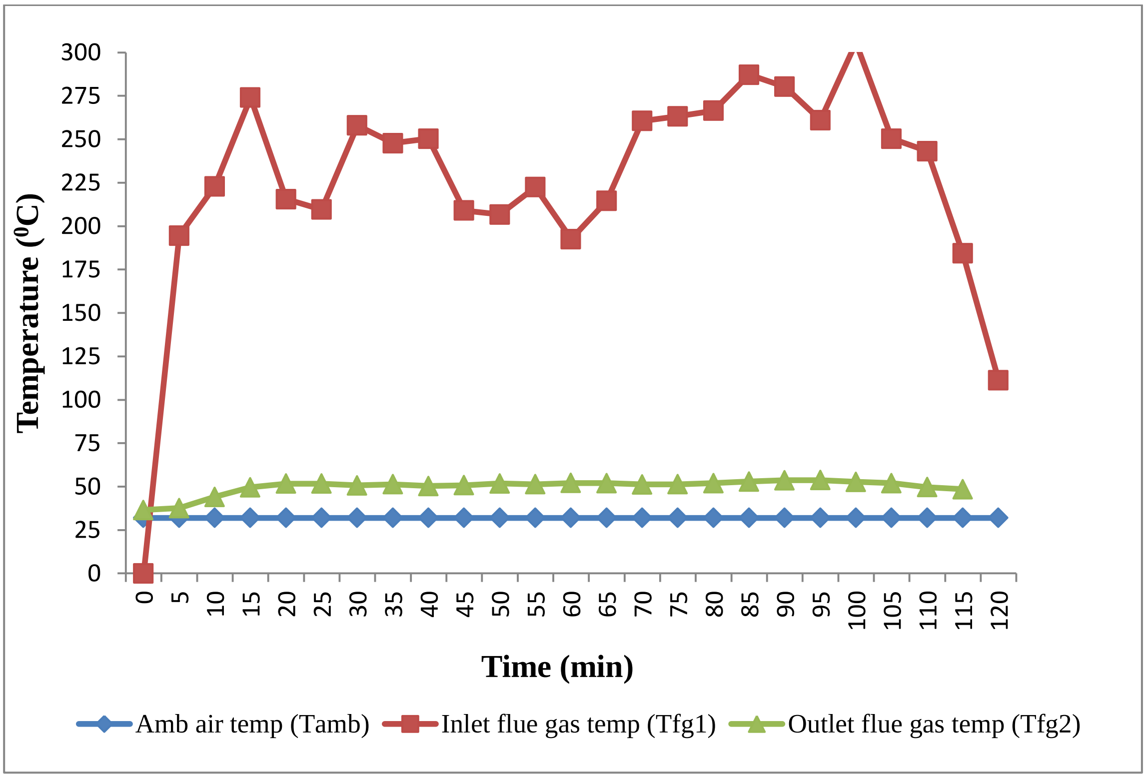

Fig.4.5 Variation of flue gas temperature (Free air supply test) at no load

It was observed that, the average flue gas temperature (T_{fg1}) at outlet of water heater was found to be 234.62 ºC. The average flue gas temperature (T_{fg2}) at outlet of flue gas at exit chimney was found to be 49.96 ºC. The mass of flue gas liberated from the water heater was estimated to be 40.97 kg. The average temperature absorb in the drying system was about 184.66 ºC, which was used to generate the hot air for drying application. The significant variation in inlet flue gas temperature may be due to poor controlled combustion process at combustion chamber. The exit flue gas temperature was observed to be constant due to proper flue gas channelling and retention of heat in drying system.

b. Variation of air temperature

The temperature of the air was recorded at different locations of the composite unit during stagnation temperature test. The air temperature at inlet of drying chamber (T_i), temperature above the 1st tray (T_{t1}), temperature above the 2nd tray (T_{t2}) and temperature at exit chimney (T_{ex}) was measured and variation is shown in Fig 4.6.

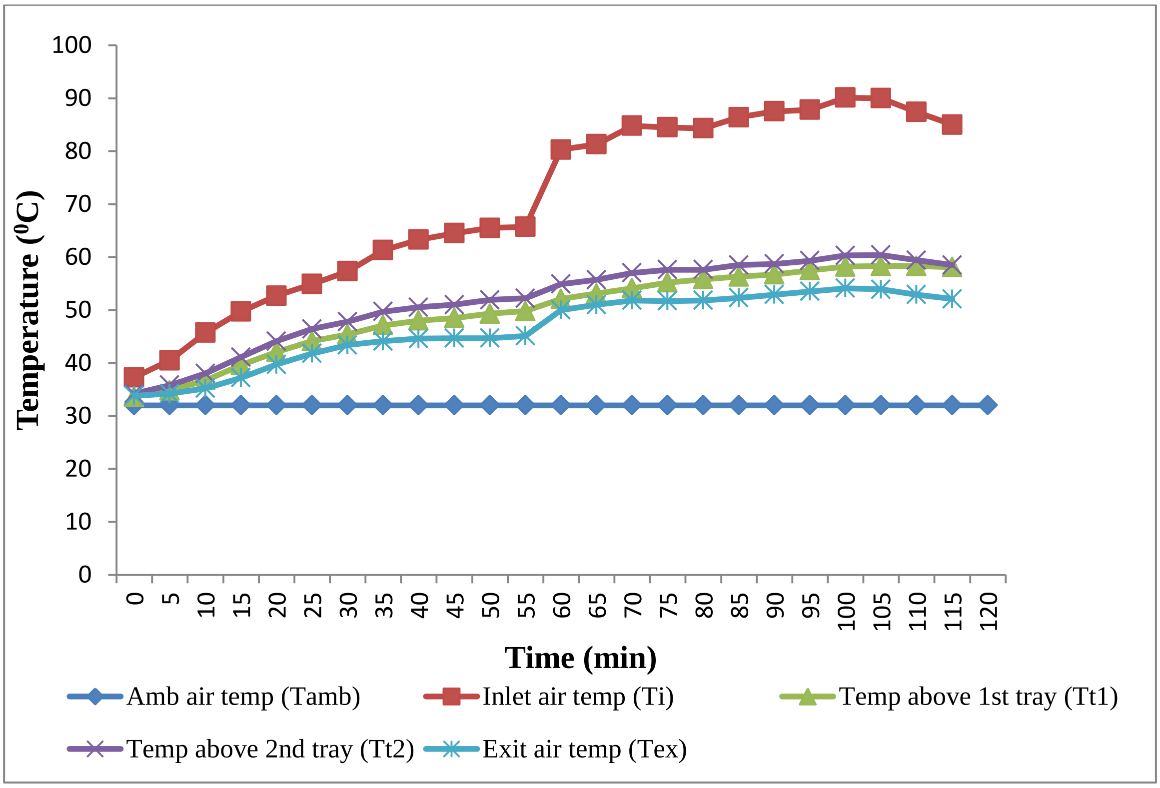

Fig.4.6 Variation of air temperature (free air supply test) at no load

It was observed that the average inlet air temperature (T_i) was fond to be 70.32 ºC. The average temperature over the 1st tray (T_{t1}) was found to be 49.69 ºC. The average temperature over 2nd tray (T_{t2}) was found to be 51.69 ºC. The average exit air temperature (T_{ex}) was fond to be 46.52 ºC. The suitable air temperature (above 45 ºC) for drying of agriculture products was achieved after 20 minutes of operation and remains constant throughout the test run. The mass of air heated during the test was estimated to be 12.98 kg with average temperature rise of 18 ºC over ambient.

The mass of fuel burnt, water heated, operating time, mass of flue gas and mass of air during the test run and average temperature at different location were used to estimate the different efficiencies of the composite system. The average thermal efficiency of water heater during free air supply test was found to be 31.95 %. The average drying efficiency of flue gas based dryer during no load test at free air supply condition was found to be 6.78 %. The overall efficiency of composite unit on no load at free air supply condition was estimated as 32.98 %.

The increase in efficiency of composite unit (6.78 %) over thermal efficiency of water heater (31.95 %) revealed the advantage of reutilization of flue gases for drying application with liberation of cold flue gases (49.96 ºC) into atmosphere as compared to 300 ºC during single unit for water heating.

4.3.1.4 Forced circulation test

Air was supplied by D.C. fan through inlet and outlet was opened. The operating parameters recorded during the test are summarized in Appendix-G-4.

a. Variation of flue gas temperature

The temperature of the flue gas was measured from starting of the test to the end of the test of composite unit. The variation of flue gas temperature with respect to operating time is shown in Fig 4.7.

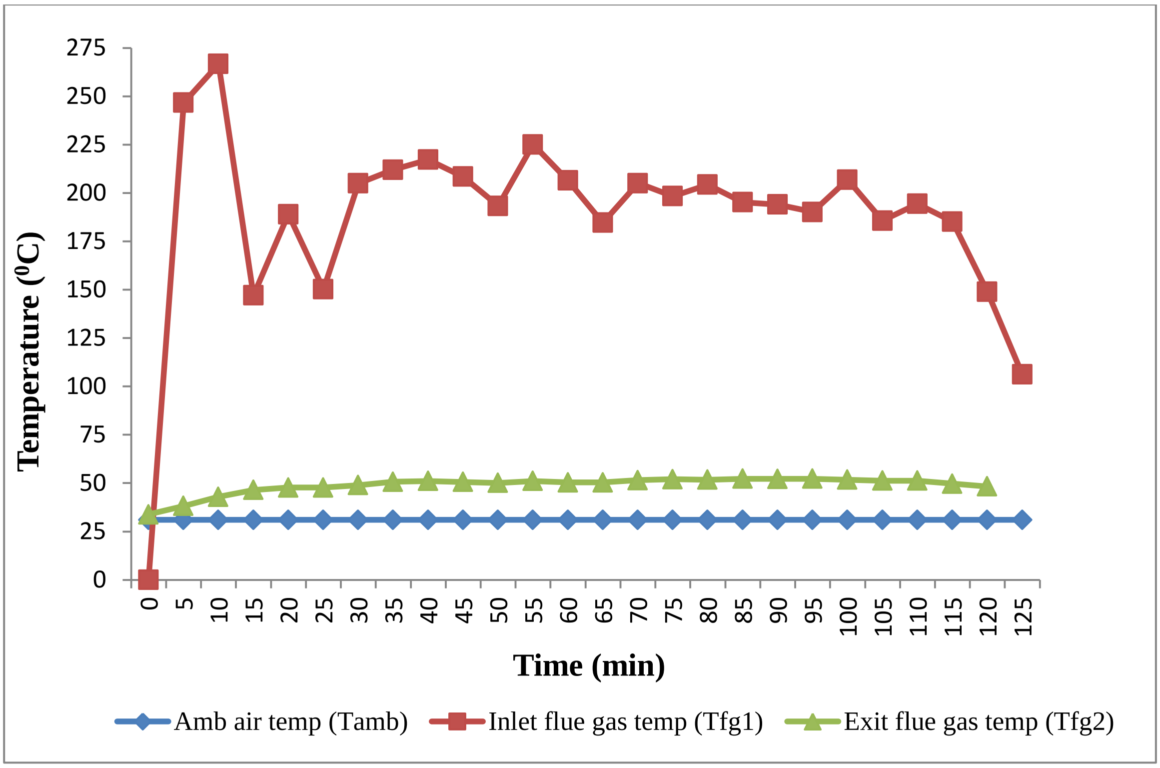

Fig.4.7 Variation of flue gas temperature (Forced circulation test) at no load

It was observed that, the average flue gas temperature (T_{fg1}) at outlet of water heater was found to be 194.66 ºC. The average flue gas temperature (T_{fg2}) at outlet of flue gas at exit chimney was found to be 48.98 ºC. The mass of flue gas liberated from the water heater was estimated to be 40.97 kg. The average temperature absorb in the drying system was about 145.68 ºC, which was used to generate the hot air for drying application. The exit flue gas temperature was observed to be constant due to proper flue gas channelling and retention of heat in drying system.

b. Variation of air temperature

The temperature of the air was recorded at different locations of the composite unit during stagnation temperature test. The air temperature at inlet of drying chamber (T_i), temperature above the 1st tray (T_{t1}), temperature above the 2nd tray (T_{t2}) and temperature at exit chimney (T_{ex}) was measured and variation is shown in Fig 4.8.

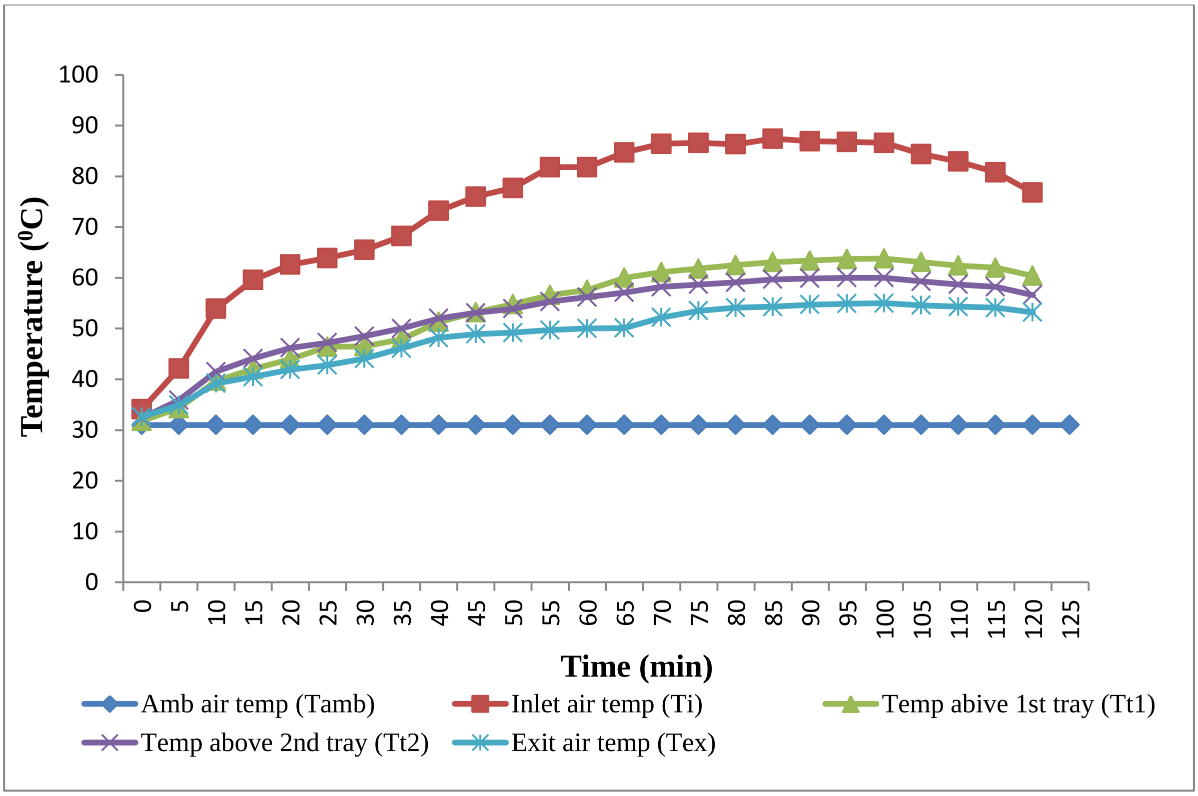

Fig.4.8 Variation of air temperature (forced circulation test) at no load

It was observed that the average inlet air temperature (T_i) was found to be 74.28 ºC. The average temperature over the 1st tray (T_{t1}) was found to be 54.13 ºC. The average temperature over 2nd tray (T_{t2}) was found to be 52.87 ºC. The average exit air temperature (T_{ex}) was fond to be 48.52 ºC. The suitable air temperature (above 45 ºC) for drying of agriculture products was achieved after 10 minutes of operation and remains constant throughout the test run. The mass of air heated during the test was estimated to be 12.98 kg with average temperature rise of 20 ºC over ambient.

The average thermal efficiency of water heater during forced circulation test was found to be 31.01 %. The average drying efficiency of flue gas based dryer during no load test at forced circulation condition was found to be 12.27 %. The overall efficiency of composite unit on no load at forced circulation condition was estimated as 32.48 %.

The increase in efficiency of composite unit (12.27 %) over thermal efficiency of water heater (31.01 %) revealed the advantage of reutilization of flue gases for drying application with liberation of cold flue gases (48.98 ºC) into atmosphere as compared to 300 ^{0}C during single unit for water heating.

4.3.1.5 Effect of air supply on performance of composite unit

Effect of air supply on performance of composite unit was estimated by comparison within 4 combinations of test at no load condition as shown in Table 4.4.

Table 4.4 Testing parameters of composite unit

Test / Parameters	Stagnation temperature	Partial air flow test	Free air supply test	Forced circulation
Air flow rate, Q_a , kg/hr	4.83	6.49	6.49	8.18
Boiler efficiency, %	32.1	31.57	31.95	31.01
Heat in air, kcal	92.06	99.68	118.37	168.83
Heat in flue gas, kcal	1863.16	1620.97	1743.49	1375.94
Dryer efficiency, %	4.94	6.15	6.78	12.27
Overall efficiency, %	32.76	32.44	32.98	32.48

It was observed that, the mass of air at stagnation temperature test, partial air flow test, free air supply test and forced circulation test was found to be 4.83 kg/hr, 6.49 kg/hr, 6.49 kg/hr and 8.18 kg/hr, respectively. Boiler efficiency was found to be 32.1 %, 31.57 %, 31.95 % and 31.01 % at stagnation temperature test, partial air flow test, free air supply test and forced circulation test respectively. Heat in air was found to be 92.06 kcal, 99.68 kcal, 118.37 kcal and 168.83 kcal at stagnation temperature test, partial air flow test, free air supply test and forced circulation test respectively.

It was revealed that, heat in air was increased with the increase in mass flow of air inside the drying chamber. The drying efficiencies was found to be maximum (12.27 %) at forced circulation tests. The overall efficiency of composite unit was found to be 32.76 %, 32.44 %, 32.98 % and 32.48 % at stagnation temperature test, partial air flow test, free air supply test and forced circulation test respectively. It was observed that drying efficiency and overall efficiency of composite unit was increased with the increase in mass flow rate of air through the drying system.

4.3.2 Load testing of composite unit

Load test was carried out to dry the onion slices by operating the unit on forced circulation mode for 4 hrs. The operating parameters recorded during the test are summarized in Appendix-H.

a. Variation of flue gas temperature

The temperature of the flue gas was measured from starting of the test to the end of the test of composite unit. The variation of flue gas temperature with respect to operating time is shown in Fig 4.9.

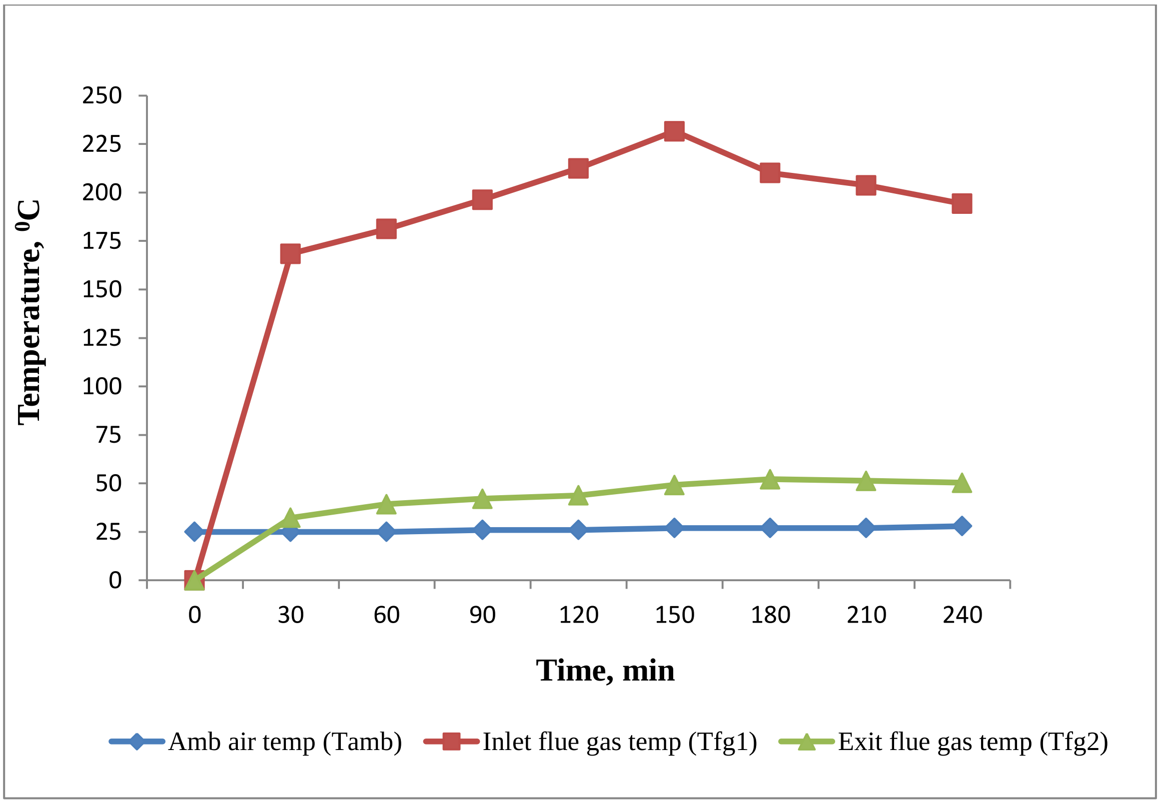

Fig.4.9 Variation of flue gas temperature at load test

It was observed that, the average flue gas temperature (T_{fg1}) at outlet of water heater was found to be 199.75 ºC. The average flue gas temperature (T_{fg2}) at outlet of flue gas at exit chimney was found to be 45.05 ºC. The mass of flue gas liberated from the water heater was estimated to be 81.95 kg. The average temperature absorb in the drying system was about 154.7 ºC, which was used to generate the hot air for drying application. The significant variation in inlet flue gas temperature may be due to poor controlled combustion process at combustion chamber. The exit flue gas temperature was observed to be constant due to proper flue gas channelling and retention of heat in drying system.

b. Variation of air temperature

The temperature of the air was recorded at different locations of the composite unit during stagnation temperature test. The air temperature at inlet of drying chamber (T_i), temperature above the 1st tray (T_{t1}), temperature above the 2nd tray (T_{t2}) and temperature at exit chimney (T_{ex}) was measured and variation is shown in Fig 4.10.

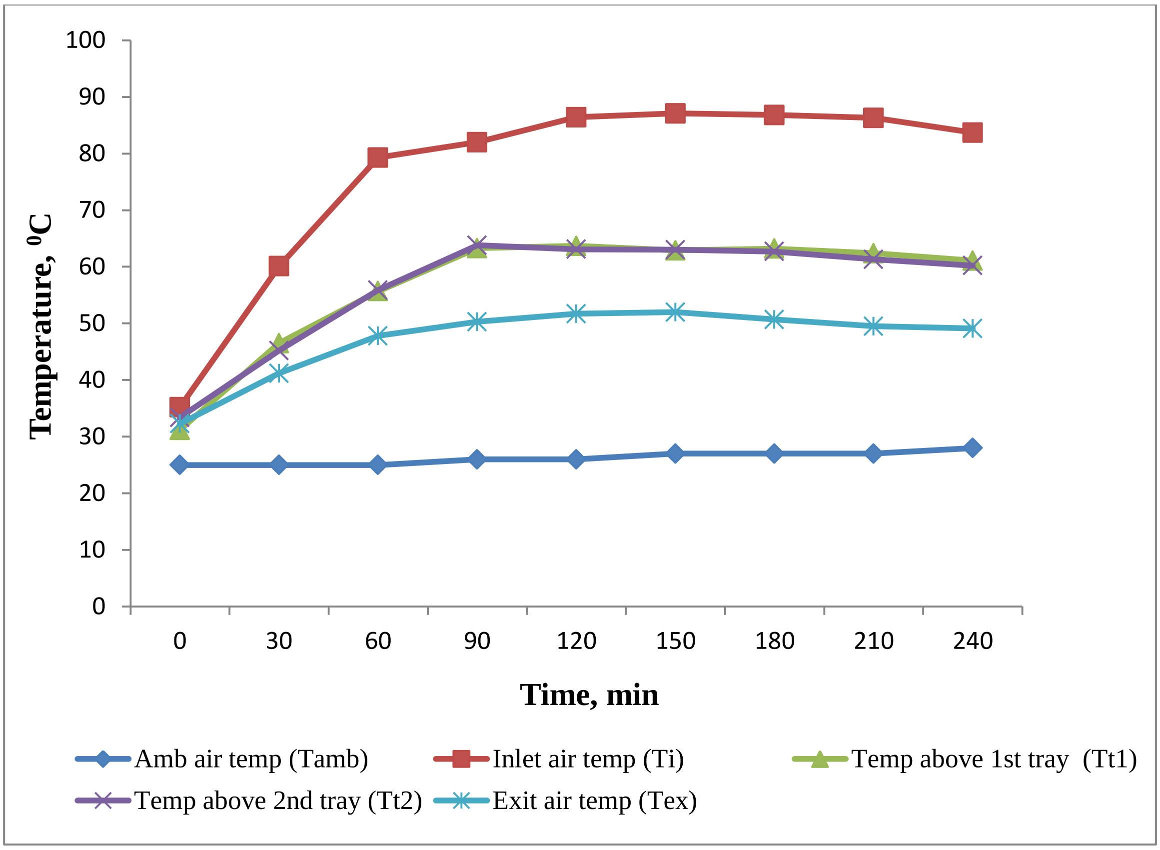

Fig.4.10 Variation of air temperature at load test

It was observed that, the average inlet air temperature (T_i) was found to be 76.32 ºC. The average temperature over the 1st tray (T_{t1}) was fond to be 56.66 ºC. The average temperature over 2nd tray (T_{t2}) was fond to be 56.51 ºC. The average exit air temperature (T_{ex}) was fond to be 47.17 ºC. The mass of air heated during the test was estimated to be 32.72 kg with average temperature rise of 20 ºC over ambient.

c. Variation of moisture content

Variation of moisture content was measured from starting of the test to the end of the test of composite unit. The variation of moisture content with respect to operating time is shown in Fig 4.11.

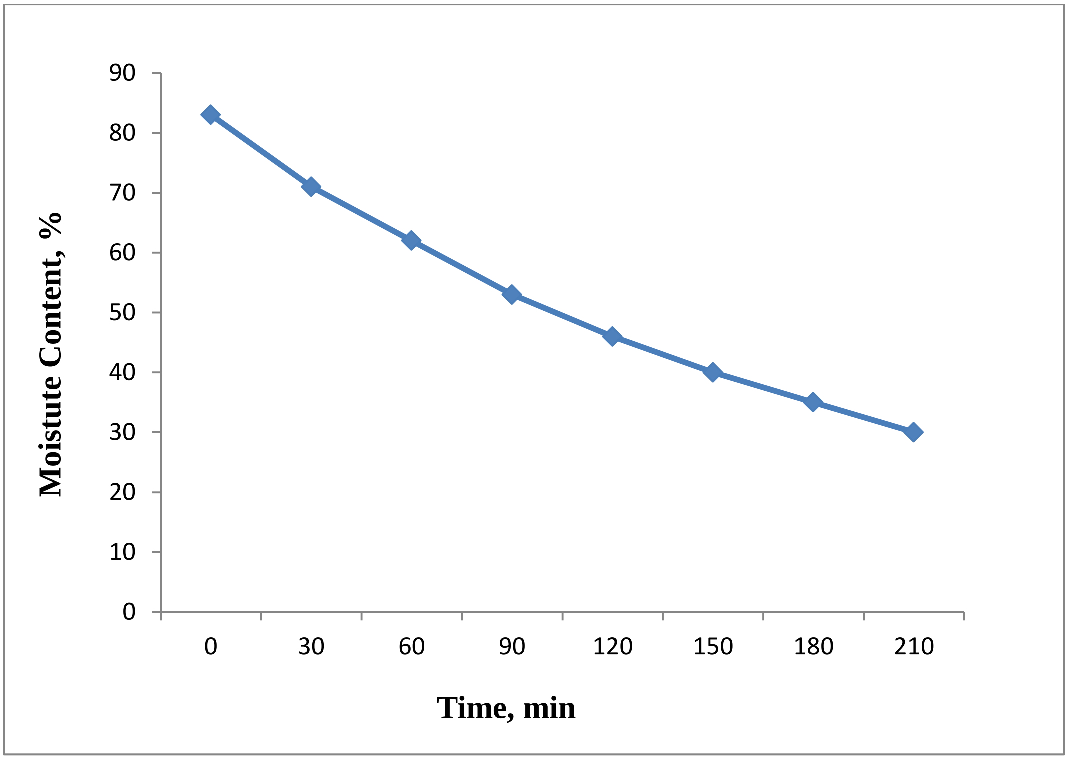

Fig.4.11 Variation of moisture content at load test

It was observed that, moisture content (% wb) of the onion slices reduced from 83% (wb) to 30.4% (wb) in 4 hr duration inside the biomass dryer. The variation of moisture content with the drying time revealed the falling rate drying. Drying curves exhibited steeper slope indicating the higher drying rate. The overall mass of water evaporated during the drying test was estimated to be 3.05 kg.

The average thermal efficiency of water heater during load test was found to be 31.95 %. The average drying efficiency of flue gas based dryer during load test was found to be 23.99 %. The overall efficiency of composite unit at load test was estimated as 34.99 %.

The increase in efficiency of composite unit (23.99 %) over thermal efficiency of water heater (31.95 %) revealed the advantage of reutilization of flue gases for drying application with liberation of cold flue gases (45.05 ºC) into atmosphere as compared to 300 ºC during single unit for water heating.

4.4 Economic evaluation of composite water heater and dryer

The economic feasibility of the composite unit was studied and compared with electricity. Based on the economic study, the different economic parameters of the composite unit are summarized as below (Appendix-I).

4.4.1 Net present worth

The net present worth of total cash inflow and outflow for composite unit with feed stocks was calculated (Appendix-H). The Net present worth of total cash inflow and outflow was found to be ₹ 30461.5 /-

4.4.2 Benefit-cost ratio

The benefit cost ratio was calculated by dividing present worth of benefit stream with the present worth of cost stream and found to be 1.05.

4.4.3 Pay-back period

The pay-back period of composite water heater and dryer was found to be 3.03 months for the initial investment of composite unit. The pay-back period less than one year revealed the economical feasibility of the composite water heater and dryer.

V. SUMMARY AND CONCLUSIONS

5.1 Summary

Biomass is an important source of energy accounting for about one third of the total fuel used in India. Large amount of heat in terms of flue gases were escaped in the atmosphere from the biomass based water heater which was reutilized for the drying purpose. Performance of water heater was carried out to estimate the heat available in the flue gases and thermal efficiency of water heater. The flue gas based dryer was developed and evaluated.

The performance of the composite unit was carried out to estimate the different operating parameters of water heater (boiler) like quantity of water heated, temperature rise of water, fuel consumption rate, flue gas temperature and thermal efficiency. The performance of composite unit was carried out in terms of no load test and full load tests to record various operating parameters like temperature of inlet and outlet flue gases, inlet and outlet air temperature, temperature inside the drying chamber, etc. The no load test was carried out at four different combinations of air supply viz. stagnation temperature, partial air flow, free air supply and air velocity (1 m/s) at forced circulation mode. Load testing was carried out by loading the dryer with onion slices.

It was revealed that, tests taken over forced circulation mode was more efficient than the others. The economics of composite unit was carried out by using different economic indicators.

The performance evaluation of composite water heater and dryer revealed that,

1. The higher amount of fixed carbon content (21.26 per cent), lower ash content (2.03 per cent) and higher calorific value (3040 kcal kg-1) of babul (*Acacia auriculiformis*) revealed its suitability for composite unit.
2. The average flue gas temperature, heat available in flue gases and mass of flue gases was found to be 333 ºC, 1515.5 kcal/hr and 20.50 kg/hr respectively.
3. Thermal efficiency of water heater was found to be 26.64 %.
4. During no load test, at stagnation temperature condition, the boiler efficiency, dryer efficiency and overall efficiency of composite unit was found as 32.1 %, 4.94 % and 32.76 % respectively.

5. At partial air flow test, boiler efficiency, dryer efficiency and overall efficiency of composite unit was found as 31.57 %, 6.15 % and 32.44 % respectively.
6. At free air supply test, boiler efficiency, dryer efficiency and overall efficiency of composite unit was found as 31.95 %, 6.78 % and 32.98 % respectively.
7. At forced circulation test, boiler efficiency, dryer efficiency and overall efficiency of composite unit was found as 31.01 %, 12.27 % and 32.48 % respectively.
8. As the air flow rate increases, the efficiency of the composite unit increases. Hence it reveals that, forced circulation method was more efficient than others.
9. In the load test onion slices dried from 83 % (w.b.) moisture content to 30 % (w.b) moisture content. In this boiler efficiency, drying efficiency and overall efficiency was found to be 31.95 %, 23.99 % and 34.99 % respectively.
10. The economic evaluation of composite unit revealed that, the net present worth (₹), benefit-cost ratio and payback period was found to be ₹ 30461.5 /-, 1.05 and 3.03 months, respectively and revealed its economic feasibility for water heating and drying application.

5.2 Conclusion

The study revealed that, the thermal efficiency of biomass based water heater was increased by 8.35 % due to reutilization of exit flue gas for drying operation. The temperature of exit flue gas reduced from 333 ºC to 50 ºC, which lead to environmental protection. The newly developed composite unit was economically feasible with payback period of 3.03 months.

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APPENDICES

APPENDIX – A

4. Proximate analysis of selected samples- Subabul (*Acacia auriculiformis*)

Sample	W_1, (g)	W_2, (g)	W_3, (g)	W_4, (g)	W_5, (g)
T_1	32.10	33.10	33.01	32.22	32.13
T_2	46.89	47.88	47.83	47.00	46.91
T_3	32.94	33.95	33.89	33.00	32.96

Sr. No.	Parameters	Average Values, %
1.	Moisture content	7.05
2.	Volatile matter	69.65
3.	Ash content	2.03
4.	Fixed carbon	21.26

APPENDIX – B

Ultimate Analysis of Subabul (*Acacia auriculiformis*):

1. % C = 0.97 C + 0.7 (VM − 0.1 A) − M (0.6 − 0.01M)

= 0.97 × 21.2612 + 0.7 (69.65 − 0.1 × 2.0314) – 11.33(0.6 − 0.01 × 7.0574)

= **65.49%**

2. % H_2 = 0.036 C + 0.086 (VM − 0.1 × A) − 0.0035 M^2 (1− 0.02M)

= 0.036×21.2612+0.086(69.65 − 0.1× 2.0314) − 0.0035$(7.0574)^2$ (1− 0.02× 7.0574)

= **6.58 %**

3. % N_2 = 2.10 − 0.020 VM

= 2.10 − 0.020 × 69.65

= **0.70 %**

4. % O_2 = 100 − (C + H_2 + N_2)%

= 100 − (65.499+ 6.588 +0.707)

= **27.20 %**

Values of Ultimate analysis:

Sr. No.	**Component**	**Values, %**
1.	Carbon	65.49
2.	Hydrogen	6.58
3.	Nitrogen	0.70
4.	Oxygen	27.20
5.	Calorific value, kcal/kg	3040

APPENDIX – C

Performance evaluation of biomass water heater

Biomass used: Subabul (***Acacia auriculiformis)***

Sr. No.	**Parameters**	**T1**	**T2**	**T3**	**Average**
	Quantity of water heated, lit	27	27	27	27
	Initial temperature of water, ºC	30	27	27	28
	Final temperature of water, ºC	60	62	61	61
	Operating time, min	30	40	40	35
	Fuel consumption, kg	1.25	1.32	0.746	1.10
	Fuel consumption rate, kg/hr	2.5	1.98	1.11	1.89
	Thermal efficiency, %	24.22	28.25	27.45	26.64
	Flue gas temperature, ºC	375	332	292	333

Temperature profile of biomass water heater:

Test No.	**Sr. No.**	**Time, min**	**Temperature of Water, ºC**	**Fuel Quantity, kg**	**Flue Gas Temperature, ºC**
T1	1	0	30	0	0
	2	10	40	0.5	310

	3	20	48	0.5	415
	4	30	60	0.25	400
Avg.				**1.25**	**375**
T2	1	0	27	0	0
	2	10	32	0.5	290
	3	20	40	0	350
	4	30	52	0.5	388
	5	40	62	0.32	300
Avg.				**1.32**	**332**
T3	1	0	27	0	0
	2	10	45	0.5	250
	3	20	51		310
	4	30	55	0.246	308
	5	40	61		300
Avg.				**0.74**	**292**
Average		**35**		**1.10**	**333**

APPENDIX – D

Estimation of heat in flue gas (BEE- 2008)

a. **Theoretical Air Required for Combustion**

Theoretical air required for complete combustion = $[(11.6 \times C) + \{34.8 \times (H_2 - O_2/8)\} + (4.35 \times S)]/100$ kg/kg of fuel

$=[(11.6\times65.499)+\{34.8\times(6.588-27.206/8)\}+(4.35\times0)]/100$

= **8.70** kg/kg fuel

b. **% Excess Air** = 20 %

c. **Actual Mass of Air Supplied**

Actual mass of air supplied = {1 + EA/ 100} × Theoretical air

= {1 + 20/ 100} × 8.70

= **10.44** kg/kg fuel

d. **Actual Mass of** = Mass of CO_2 + Mass of N_2 content in fuel + Mass of N_2 in the

Dry Flue Gas combustion air supplied + Mass of O_2 in flue gas

$$= \frac{0.65 \times 44}{12} + 0.00707 + \frac{10.44 \times 77}{100} + \frac{(10.44 - 8.70) \times 23}{100}$$

= **10.84** kg/kg of fuel

e. Heat Available in Dry Flue Gas:

$Q = m \times c_p \times \Delta T$

$= 10.84 \times 0.24 \times (333 - 25)$

= 801.86 kcal/kg of fuel

f. Quantity of Flue Gas (Volume):

1. Mass of $CO_2 = \frac{0.65 \times 44}{12}$

= 2.40 kg

= 5.29 lb

∴ Volume of $CO_2 = 5.29 \times 359 \times \frac{2.15}{44}$

$= 92.87\ ft^3$

$= 2.63\ m^3$ $(1\ ft^3 = 0.02\ m^3)$

2. Mass of N_2 content in fuel = 0.00707 kg = 0.015 lb

∴ Volume of $N_2 = 0.01558 \times 359 \times \frac{2.15}{28}$

$= 0.42\ ft^3$

$= 0.012\ m^3$

3. Mass of N_2 content in combustion air $= \frac{10.44 \times 77}{100}$

= 8.038 kg

= 17.72 lb

∴ Volume of N_2 in combustion air $= 17.72 \times 359 \times \frac{2.15}{28}$

$= 488.54\ ft^3$

$= 13.83\ m^3$

4. Mass of O_2 in flue gas $= \frac{(10.44 - 8.7) - 23}{100}$

= 0.40 kg

= 0.88 lb

∴ Volume of O_2 in flue gas $= 0.88 \times \frac{359}{32} \times 2.15$

$= 21.28\ ft^3$

$= 0.60\ m^3$

∴ Total volume of flue gas = Volume of CO_2 + Volume of N_2 in fuel + Volume of N_2

in combustion air + Volume of O_2 in flue gas

$= 2.63 + 0.012 + 13.83 + 0.60\ m^3$

= 17.07 m^3/kg

5. **Total Heat Available:**

∴ Total heat available in dry flue gas = Q × Quantity of fuel/ batch

= 801.86 x 1.10

= **886.29 kcal/batch**

I. **Heat available in flue gas = 1515.5 kcal/hr**

II. **Volume of flue gas = 17.07 m^3/kg of fuel= 32.26 m^3 /hr**

III. **Mass of flue gas = 10.84 × 1.89 = 20.50 kg/hr**

APPENDIX-E

5. Design of flue gas based dryer

1. Design Consideration and assumptions

Product data and ambient conditions

Sr. No.	Parameters		Range	Assumption
1.	Location CAET, Dapoli, Maharashtra	Φ		$17^0 45'$ N Latitude, $73^0 26'$ E Longitude
1.	Product to be dried			Food-Vegetable etc
4.	Bulk density of material	ρ_{ck}	300-800 kg/m^3	600 kg/m^3
5.	Specific heat of product	Cp_{ck}	0.6-0.9 Kcal/Kg^{0}C	0.8 Kcal/Kg^{0}C
6.	Initial moisture content	M_i	65-75 % (w. b.)	70 % (w. b.)
7.	Final moisture content	M_f	12-17 % (w. b.)	15 % (w. b.)
8.	Drying duration per batch	t_d		3 hr
9.	Operating temperature	T	50- 70°C	60°C
10.	Ambient air temperature	T_{amb}	20-30°C	25°C
11	Ambient Relative humidity	RH_{amb}	70-90 %	70 %

13.	Latent heat of vaporization	λ	540 Kcal/kg
17.	Moisture pickup efficiency	η	75 % (Assumed)

Drying with heated air using Psychometric chart (Bansal & Klemann,1990)

	Properties	**Ambient air**	**Drying air**	**Exit air**
I.	Temperature	25 ^oC	60 ^oC	35 ^oC
II.	Relative humidity	70 %	11 %	70 %
III.	Sp. Volume, m3/kg	0.865	0.963	0.905
IV.	Humidity ratio, kg/kg of air	0.014	0.014	0.0245
V.	Enthalpy, kcal/kg	14.5 (60.71 KJ/kg)	23.7 (99.20 KJ/kg)	23.7 (99.7 KJ/Kg)

1. **The mass of water to be removed during drying, M_w kg** (Basunia and Abe, 2001)

$$M_w = \frac{(70-15)}{(100-15)} \times 1 = 0.6 Kg$$

Total Water in product = 0.6 kg/kg of product

Dry matter content at 0 % moisture content = 0.3 Kg

Final weight of product at 15 % moisture = DM x 100/100-15 = 0.353 Kg

2. **Total energy required, Q, kcal**

$$Q = (1 \times 0.8 \times 35) + (0.6 \times 1 \times 35) + (0.6 \times 540)$$

$$Q = 373 Kcal/kg$$

Total energy required = 373 kcal/ kg.

3. **Volumetric flow rate of air, Q_a , M^3 / hr**.

$$Q_a = \frac{M_w}{\rho a(Hf - Hi)}$$

$$Q_a = \frac{0.6}{1.252(0.0245 - 0.014)} = 45.64\ m3/hr$$

Volumetric flow rate of air = 45.64 m^3/hr

4. **Quantity of product dried:**

Considering heat available from flue gas as 1000 kcal/ hr and assuming moisture pickup efficiency as 75 %,

$$Q_p = \frac{1000}{373} \times 0.75 = 2\ kg/hr$$

Considering the operation of water heater continuously for 3 hr in a day

Total drying capacity = 2× 3 = 6 kg/hr**Drying area:**

Considering the bulk density of product as 600 kg/m^3, thickness of single layer of product (0.02 m) and length to width ratio of tray as 1:1,

No. of tray = 2

Product on tray = 3 kg/ Tray

Width of tray = 0.5 m

Length of tray = 0.5 m

APPENDIX – F

Fabrication cost of flue gas based dryer

Sr. No.	**Particulars**	**Specifications, mm**	**Material**	**Quantity**	**Amount, ₹**
1.	Drying chamber Inner box Outer box	 500×500×300 550×550×350	GI sheet 18 SWG 16 SWG	 1 1	 1325 /- 2325 /-
2.	Heat exchanger Square pipe Circular pipe	 1200 × 100 × 100 50 mm Ø	 GI 16 SWG MS	 1 1	 475 /- 225 /-
3.	Outlet chimneys Flue gas exit Moist air exit	 25 mm Ø 25 mm Ø	 GI sheet	 2	 125 /-
4.	Drying trays	500×500	MS wire mesh	2	425 /-

5.	Opening door	300 × 250	GI 16 SWG	2	175 /-
6.	Stand	Height- 1100	MS angle	1	925 /-
7.	Labour cost				3000 /-
8.	Insulation				200 /-
9.	Miscellaneous				300 /-
10.	Biomass water heater				6000 /-
	Total cost				**15500 /-**

APPENDIX – G

1. Testing of composite water heater and dryer (Stagnation temperature)

Time	T_{amb}, °C	T_{fg1}, °C	T_{fg2}, °C	T_i, °C	T_{t1}, °C	T_{t2}, °C	T_{ex}, °C	T_{water}, °C
0	29	0	29.6	28.9	28.7	28.8	29.7	29.9
5	29	170	30.8	31.8	29.3	30.1	30	30
10	29	210.2	37.4	39.4	32.1	33.1	30.8	35.1
15	29	177	40.2	42.9	35.3	36.7	32.8	37.2
20	29	180	41.9	44.5	37	38.5	34.2	38.8
25	29	201.2	45.6	46.7	39.9	41.6	36.6	48.9
30	29	208.1	47.7	48.6	41.1	42.8	37.4	50.2
35	29	229	49.5	52.9	43	45	39.6	54.9
40	29	245.1	49.8	54.2	45.2	47.5	41.9	58.8
45	29	264	50	57.2	45.5	47.7	42.1	63.9
50	29	230	49.5	58.8	46.9	48.9	42.8	
55	29	214	49.4	58.4	47.4	49.5	42.6	
60	29	218	48.7	62.9	47.9	49.9	43	
65	29	198	49	65	48	50.2	43.2	
70	29	235.8	49.8	66	48.4	50.7	43.3	
75	29	236.1	50.5	65.9	48.6	51	43.2	
80	29	230.2	51.1	68.2	49.5	51.9	43.3	
85	29	230.3	52.3	69	50.6	53	43.6	
90	29	224.7	50.3	67.2	51.2	53	44.1	
95	29	213	52	65.5	51.2	53	44.1	
100	29	231.3	52.7	67.2	51.7	53.6	44.7	

105	29	223.4	53.1	67.8	52	54.1	44.9	
110	29	203	54	67.9	52.4	54.3	45.3	
115	29	213.2	52.9	69.4	53	54.8	45.5	
120	29	218	52.9	69.1	53	54.9	45.6	
125	29	216.8	53.5	70.5	53.2	55.1	45.7	
130	29	215	53.1	69.5	53.3	55	45.5	
135	29	182	51.8	67.6	53.2	54.7	45.1	
140	29	158	50.5	69.7	53.3	54.5	44.9	
145	29	125.1	47.9	69.8	53.1	53.7	44.1	
150	29	112.1	46.2	69.7	53	53.2	43.8	
Average	29	207.08	48.80	60.77	47.31	49.06	41.79	

i. Fuel: Subabul (*acacia auriculiformis*)

ii. Operation Time: 2.5 hr

iii. Fuel consumption: 4.7 kg

iv. Quantity of water: 135 lit

v. Mass of air = 12.07 kg

vi. Mass of flue gas = 50.9 kg

APPENDIX – G

2. Testing of Composite Water Heater and Dryer (Partial air flow)

Time	T_{amb}, °C	T_{fg1}, °C	T_{fg2}, °C	T_{i}, °C	T_{t1}, °C	T_{t2}, °C	T_{ex}, °C	T_{water}, °C
0	31	0						29.4
5	31	158	35	37.1	32.8	33.5	32.5	34.2
10	31	145	39.7	41.8	35.9	36.5	34.2	38.6
15	31	208	40.6	42.5	37.2	37.6	35.1	42.2
20	31	230.2	45.5	46.8	40.2	40.8	37.5	45.3
25	31	246.7	48.7	47.6	42.6	43	39.8	49.2
30	31	265	52.3	50.2	44.6	45.1	42.1	52.2
35	31	244	53.8	53.1	47.2	48.1	44.6	61.2
40	31	268	54.2	54.2	48.9	49.9	45.5	63
45	31	260.2	53.9	56.9	50.2	51.3	46.6	
50	31	260	52.5	58.1	50.8	51.9	47.2	
55	31	259.4	54.1	59.3	51.3	52.4	47.4	
60	31	267.5	55.5	60.4	52.4	53.6	48.3	

65	31	249.3	54.1	73.9	54.7	55.3	51.6	
70	31	246.5	54.5	75.6	56.2	56.4	53.3	
75	31	215	53	77.4	56.8	56.5	53.9	
80	31	227.5	52.6	77.6	56.9	56.4	53.8	
85	31	208.4	52.1	76.8	56.8	53.5	52.3	
90	31	234.2	53.3	74.3	56.3	55.9	53.2	
95	31	210.7	52.9	76.6	56.7	56.1	53.3	
100	31	208.6	52.6	78	57	56.2	53.4	
105	31	190.2	52.5	74.6	56.4	55.8	53.1	
110	31	201.8	52.9	71.7	56.1	55.3	53.8	
115	31	172.2	52.8	71.4	56	55.4	52.9	
120	31	160.4	52.6	71.9	55.8	55.2	52.6	
Average	31	222.36	50.90	62.82	50.40	50.48	47.41	

i. Fuel: Subabul (*acacia auriculiformis*)

ii. Operation Time: 2 hr

iii. Fuel consumption: 3.78 kg

iv. Quantity of water: 108 lit

v. Mass of air = 12.98 kg

vi. Mass of flue gas = 40.97 kg

APPENDIX – G

3. Testing of Composite Water Heater and Dryer (Free air supply test)

Time	**T_{amb}, ^oC**	**T_{fg1}, ^oC**	**T_{fg2}, ^oC**	**T_i, ^oC**	**T_{t1}, ^oC**	**T_{t2}, ^oC**	**T_{ex}, ^oC**	**T_{water}, ^oC**
0	32	0						31.4
5	32	194.5	36.5	37.3	33.6	34.2	33.8	34.4
10	32	222.9	37.6	40.5	34.8	35.8	34.2	37.8
15	32	274	44.1	45.7	36.7	38	35.2	44.7
20	32	215.5	49.6	49.7	39.6	41.1	37.2	45.9
25	32	209.5	51.7	52.7	42.1	44.1	39.7	52.4
30	32	258	51.7	54.9	44.1	46.4	41.8	53.8
35	32	247.8	50.7	57.3	45.4	47.8	43.4	56.4
40	32	250.3	51.3	61.3	47.1	49.7	44.1	61.6
45	32	209	50.3	63.3	48	50.5	44.6	65.3
50	32	206.7	50.8	64.5	48.5	51	44.7	
55	32	222.4	51.8	65.5	49.3	51.9	44.7	

60	32	192.5	51.3	65.7	49.8	52.2	45.1	
65	32	214.5	52.1	80.3	52.1	54.9	50	
70	32	260.6	52	81.3	53.1	55.7	51	
75	32	263.2	51.2	84.8	54.1	57	51.8	
80	32	266.5	51.3	84.5	55.2	57.6	51.7	
85	32	287.2	52	84.3	55.8	57.6	51.8	
90	32	280.3	52.9	86.4	56.3	58.5	52.3	
95	32	261	53.6	87.5	56.7	58.7	52.9	
100	32	305.7	53.7	87.8	57.5	59.3	53.5	
105	32	250.3	52.7	90.1	58.2	60.3	54.1	
110	32	243.2	52	90	58.3	60.4	53.9	
115	32	184.3	49.7	87.4	58.3	59.4	52.9	
120	32	111.2	48.5	85	58.1	58.5	52.1	
Average	32	234.62	49.96	70.32	49.69	51.69	46.52	

i. Fuel: Subabul (*acacia auriculiformis*)
ii. Operation Time: 2 hr
iii. Fuel consumption: 3.78 kg
iv. Quantity of water: 108 lit
v. Mass of ai Mass of flue gas = 40.97 kg

APPENDIX – G

4. Testing of Composite Water Heater and Dryer (Forced circulation)

Time	T_{amb}, ^oC	T_{fg1}, ^oC	T_{fg2}, ^oC	T_i, ^oC	T_{t1}, ^oC	T_{t2}, ^oC	T_{ex}, ^oC	T_{water}, ^oC
0	31	0						29.4
5	31	246.7	33.8	34.1	31.8	32.4	32.6	34
10	31	266.7	38.2	42.1	34.3	35.9	34.9	37.8
15	31	147.1	42.9	53.9	39.7	41.5	39.2	41.9
20	31	189	46.5	59.6	42	44.1	40.5	45.1
25	31	150.2	47.7	62.6	44	46.2	41.9	49.5
30	31	205	47.7	63.9	46.4	47.2	42.8	52.7
35	31	212	49	65.5	46.5	48.5	44.1	61.1
40	31	217.2	50.7	68.2	47.9	50	46.1	62
45	31	208.5	51.1	73.2	51.3	52	48.2	
50	31	193.3	50.6	76	53.2	53.1	48.9	
55	31	225.1	50.1	77.7	54.8	53.9	49.2	
60	31	206.5	51.1	81.8	56.6	55.3	49.7	
65	31	184.6	50.4	81.8	57.6	56.2	50	
70	31	205.1	50.4	84.7	60	57.1	50.1	
75	31	198.4	51.5	86.4	61.1	58.2	52.2	
80	31	204.3	52	86.6	61.8	58.7	53.5	
85	31	195.2	51.8	86.3	62.5	59.1	54.1	
90	31	194.1	52.3	87.4	63.1	59.7	54.3	

95	31	190.2	52.2	86.9	63.4	59.9	54.7	
100	31	206.9	52.3	86.8	63.7	60	54.9	
105	31	185.7	51.8	86.6	63.8	60	55	
110	31	194.4	51.3	84.4	63.1	59.3	54.6	
115	31	185.2	51.3	82.9	62.4	58.7	54.3	
120	31	148.9	49.7	80.8	62	58.2	54.1	
125	31	106.2	48.3	76.8	60.4	56.6	53.2	
Average	31	194.66	48.98	74.28	54.13	52.87	48.52	

i. Fuel: Subabul (*acacia auriculiformis*)
ii. Operation Time: 2 hr
iii. Fuel consumption: 3.78 kg
iv. Quantity of water: 108 lit
v. Mass of air = 16.36 kg
vi. Mass of flue gas = 40.97 kg

APPENDIX – H

Load test of composite water heater and dryer (Forced circulation)

Time, min	**Wt. of product, gm**	**M.C. of product, %**	**T_i,** ^oC	**T_{t1},** ^oC	**T_{t2},** ^oC	**T_{ex},** ^oC	**T_{fg1},** ^oC	**T_{fg2},** ^oC	**T_{amb},** ^oC	**T_{water},** ^oC
0	5000	83	35.2	31.2	33.4	32.3	0	0	25	27
30	4150	71	60.1	46.5	45.2	41.2	168.4	32.3	25	50.3
60	3550	62	79.3	55.7	55.9	47.8	181.2	39.3	25	61.2
90	3100	53	82.0	63.3	63.8	50.3	196.3	42.1	26	
120	2650	46	86.4	63.7	63.1	51.7	212.5	43.8	26	
150	2300	40	87.1	62.9	63.0	52.0	231.6	49.2	27	

180	2000	35	86.8	63.2	62.7	50.7	210.1	52.1	27	
210	1750	30	86.3	62.4	61.3	49.5	203.7	51.3	27	
240	1500		83.7	61.1	60.2	49.1	194.2	50.3	28	
Avg.			**76.32**	**56.66**	**56.51**	**47.17**	**199.75**	**45.05**	**26.2**	

i. Fuel: Subabul (*acacia auriculiformis*)
ii. Operation Time: 4 hr
iii. Fuel consumption: 7.56 kg
iv. Quantity of water: 216 lit
v. Mass of air = 32.72 kg
vi. Mass of flue gas = 81.95 kg
vii. Mass of water evaporated = 4150 – 1100 = 3050 gm = 3.05 kg

APPENDIX –I

Yearly cost of operation for biomass based composite water heater and dryer.

The yearly cost of operation for biomass based composite water heater and dryer was calculated based on the following assumption:

(i) Interest rate @ 12 per cent of initial investment
(ii) Depreciation @ 10 per cent of initial investment per year
(iii) Repair and maintenance cost is about ₹ 500 per year
(iv) Discount rate is assumed 12 per cent
(v) The labor cost is taken as @₹ 120/- per day
(vi) The cost of one unit of electricity is ₹ /- 6 (for above 100 unit)

The annual use of biomass based composite water heater and dryer is assumed as 300 days per annum.

Sr.No.	Description	Values, ₹
Fixed Cost, (₹/year)		

1.	Initial investment of water heater	6000 /-
2.	Initial investment of flue gas based dryer	9500 /-
	Fixed cost	**15500 /-**
Variable Cost, (₹/year)		
3.	Fuel cost(Wood) ,(2 kg /hr × 4 hr/day×300@₹.3/kg)	7200 /-
4.	Raw material cost (Onion), (5 kg/ day × 300 @₹ 24/kg	36000 /-
5.	Labor cost,(1 labor / day × 300@₹ 120/ day)	36000 /-
6.	Depreciation	950 /-
7.	Interest	1140 /-
8.	Repair and Maintenance cost/ annum	500 /-
	Variable cost	**81790 /-**
9.	**Total cost**	**97290 /-**

Present system was compared with the conventional method of hot water i.e. electricity.

i. Electricity required to heat 200 lit water from 28 ^{o}C to 60 ^{o}C:

$$= [200 \times 1 \times (60-28)] / 860$$

$$= 7.44$$

$$\approx 8 \text{ kwh/day}$$

ii. Cost of electricity

$$= 8 \times 300 \times 6$$

= ₹ 14400 /year.

iii. Saving due to water heater

= ₹ 14400 – 7200

= ₹ 7200 /year

iv. Inflow from dried (Onion) product

Considering the 1.5 kg of dried product and selling rate as ₹ 200 /kg,

The cost of dried product = ₹ 90000 / year

Cash inflow and outflow statement of composite unit

Year	Cash outflow	PW of Cash outflow	Cash inflow	PW of Cash inflow	NPW
1.0	2.0	3.0	4.0	5.0	(5)-(3)
0.0	97290	97290.0	0.0		-97290.0
1.0	81790	73026.8	104400	93214.3	20187.5
2.0	81790	65202.5	104400	83227.0	18024.6
3.0	81790	58216.5	104400	74309.9	16093.4
4.0	81790	51979.0	104400	66348.1	14369.1
5.0	81790	46409.8	104400	59239.4	12829.5
6.0	81790	41437.4	104400	52892.3	11454.9
7.0	81790	36997.6	104400	47225.3	10227.6
8.0	81790	33033.6	104400	42165.4	9131.8
9.0	81790	29494.3	104400	37647.7	8153.4
10.0	81790	26334.2	104400	33614.0	7279.8

Total		**559421.7**		**589883.3**	**30461.5**

NPW = 30461.5

BCR = 1.05

Pay-back period = 3.03 months