Energy Conversion and Management 173 (2018) 244–261

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Design, evaluation and heat transfer analysis of novel forced draft paddy straw bale combustor using heat sink pipe networks for greenhouse heating

Biswajeet Singh, V.P. Sethi*, Mankaran Dhiman, Ashwani Sharma

Department of Mechanical Engineering, Punjab Agricultural University, Ludhiana 141004, India

ARTICLE INFO

Keywords:
Biomass combustor
Heat transfer
Heat sink pipe
Greenhouse heating
Mathematical model

ABSTRACT

In this study, first of its kind novel design of forced draft paddy straw bale combustor (FDPSBC) coupled with innovative pilot fuel injection system (PFIS) and furnace embedded internal water heat-exchanger for large scale water heating is presented. PFIS is optimized to spray 1.5 ml of diesel after every 3 min interval to achieve complete combustion of the compressed bale by maintaining the flame sustainability. Stainless steel heat-exchanger has 62 L water holding capacity circulating at the rate of 36 L per min using the heat of flue gas and has the capacity to heat 1000 L of water from 30 °C to 65 °C within three hours. Heat of combustion (> 90% combustion efficiency) was utilized to generate flue gas at 350 °C and hot water above 65 °C applied to 100 m^2 area greenhouse heating located at Punjab Agricultural University, Ludhiana (30.56°N), Punjab, India by designing two heat sink pipe networks; flue gas heat sink pipe network (FGHSPN) fabricated with galvanized iron (GI) and hot water heat sink pipe network (HWHSPN) fabricated with mild steel (MS) respectively laid inside the greenhouse for transfer of heat by radiation and free convection modes. Developed mathematical models showed that FGHSPN was able to transfer 9.6 kW (74%) and where as HWHSPN could transfer 3.38 kW (26%) of heat respectively out of the total heat (12.98 kW) transferred by both the networks to maintain the greenhouse air temperature 10 °C higher than the ambient air temperature after sunset hours as validated by experimental trials conducted in the month of November 2017. Installation cost of FDPSBC technology is Rs 5,00,000 ($8000) and with 24 h continuous operation, it can save about 80 kWh per day and can recover the 50% of installation and operating costs within five years time besides managing about 27% of the total paddy straw available in the state of Punjab (India) through useful heating applications including greenhouse heating.

1. Introduction

Global increase in energy demand coupled with limited conventional fuel options and environmental concerns have compelled the scientists to search for renewable and sustainable energy options. The main thrust areas of renewable energy development are biomass, solar, wind and small hydro. Out of these, solar, wind and small hydro are considered as clean sources for producing heat and energy.

However, for mankind biomass has always been a major source of energy and accounts for about 13% of global primary energy consumption. Biomass plays even more significant role in developing countries, particularly in the energy sector due to important source of energy for cooking in the domestic sector and thermal energy for many small and medium industries and commercial establishments [1].

All over the world, there are varieties of biomass available in the fields after the harvest of a crop. There are many examples of utilization of agricultural residues such as paddy straw for heat and power generation all over the world [2–4]. However, slagging, fouling and sintering are some of the operational difficulties of biomass (including rice straw) fired power plants [5,6]. Paddy straw is a by-product of rice farming and has variety of applications with region specific distinction such as feedstock and a bedding material for livestock, domestic fuel and as building material in rural areas [7]. In other cases compost making to support soil fertility and paper making are also practiced [8]. Even within India, paddy straw is used as animal feed in many Southern states, whereas in states like Punjab, Haryana and Andhra Pradesh paddy straw is not used as animal feed due to the availability of other fodder materials [9].

In India, about 43.95 million hectare area is under paddy producing about 106.54 million tons (MT) of rice and approximately 160 MT of straw was produced every year. In northern Indian states particularly in Punjab, 11.27 MT of rice is produced along with a total of 22 MT of paddy straw every year. But, due to surplus paddy straw and problem associated with its storage, nearly 16 MT (more than 72% of the total

* Corresponding author.
E-mail address: vpsethi@pau.edu (V.P. Sethi).

https://doi.org/10.1016/j.enconman.2018.07.085
Received 4 January 2018; Received in revised form 21 July 2018; Accepted 25 July 2018

Nomenclature

A_f	surface area of flue gas heat sink pipe (m^2)
A_{sw}, A_{nw}, A_{ew}, A_{ww}	area of south, north, east, west wall respectively (m^2)
A_{sr}, A_{nr}	area of south and north roof of greenhouse respectively (m^2)
A_w	surface area of water heat sink pipe (m^2)
C_p	specific heat of greenhouse inside air ($J\,kg^{-1}\,K^{-1}$)
g	acceleration due to gravity (ms^{-2})
Gr	Grasshoff number
h_{fg}	convective heat transfer coefficient between flue gas pipe surface and greenhouse air ($Wm^{-2}\,k^{-1}$)
h_{wg}	convective heat transfer coefficient between hot water pipe surface and greenhouse air ($Wm^{-2}\,k^{-1}$)
h_o	total convective heat transfer coefficient from north and south roofs to ambient air ($Wm^{-2}\,k^{-1}$)
h_i	total radiative heat transfer coefficient from east and west walls to ambient air ($Wm^{-2}\,k^{-1}$)
k_1, k_2, k_3	thermal conductivity of brick, ceramic wool, mild steel respectively ($Wm^{-1}\,K^{-1}$)
L_{M1}, L_{M2}	characteristic length of entry and exit pipe of FGHSPN respectively (m)
L_{f1}, L_{f2}, L_{f3}, L_{f4}	characteristic length of lateral pipes of FGHSPN respectively (m)
L_{W1}, L_{W2}	characteristic length of entry and exit pipe of HWHSPN respectively (m)
L_{w1}, L_{w2}, L_{w3}, L_{w4}, L_{w5}	characteristic length of lateral pipes of HWHSPN respectively (m)
Nu	Nusselt number
Pr	Prandtl number
Q_{rf}	radiative heat transfer from flue gas heat sink pipe (kW)
Q_{rw}	radiative heat transfer from water heat sink pipe (kW)
Q_{cf}	free convection heat transfer from flue gas heat sink pipe (kW)
Q_{cw}	free convection heat transfer from water heat sink pipe (kW)
Q_d	heat demand of greenhouse (kW)
T_{ia}, T_a	temperature of greenhouse inside air and ambient air respectively (°C)
T_{fs}	surface temperature of flue gas heat sink pipe (°C)
T_{ws}	surface temperature of water heat sink pipe (°C)
$T_{M(b)}$, $T_{L(b)}$	bulk mean temperature of main and lateral pipes of FGHSPN respectively (°C)
$T_{W(b)}$, $T_{wL(b)}$	bulk mean temperature of main and lateral pipes of HWHSPN respectively (°C)
U_1, U_2	overall heat transfer coefficient from greenhouse air to ambient air through walls and roofs respectively ($Wm^{-2}\,K^{-1}$)

Greek letters

ε_{GI}, ε_{MS}	emissivity of galvanized iron and mild steel respectively (dimensionless)
ΔT_f	rise in greenhouse inside air temperature due to radiative and convective heat transfer from flue gas heat sink pipe network (°C)
ΔT_w	rise in greenhouse inside air temperature due to radiative and convective heat transfer from water heat sink network (°C)
ν	kinematic viscosity of air at mean surface temperature ($m^2\,s^{-1}$)
μ	dynamic viscosity of greenhouse inside air ($kg\,m^{-1}\,s^{-1}$)

Subscripts

1, 2, 3, 4, 5	lateral pipe number
f	flue gas
M1, M2	flue gas main entry and exit pipe
P1, P2, P3, P4	lateral flue gas pipes
w	water
w_1, w_2, w_3, w_4, w_5	lateral hot water pipes
W_1, W_2	water main entry and exit water pipe

paddy straw production) is burnt openly in the fields to quickly prepare it for sowing the next wheat crop. Farmers typically have just about three weeks to clear it away before the wheat season begins. The straw is usually burned openly in the same fields where it was grown, in spite of regulations and knowledge of environmental and human damages [10].

Although, part of stubble and straw incorporation into the soil returns most of the nutrients and helps conserve soil nutrient reserves in the long term, yet spreading and incorporation are labor-intensive, so farmers usually adopt burning straw in fields after harvest. Burning in open fields lead to significant environmental degradation in the form of air pollution, returns few nutrients to the soil and the farmers receive no financial benefit from the residue [11]. However, complete utilization of some crop residues may lead to soil erosion and a decrease in soil organic matter [12]. At present, baling of loose paddy straw in the field (*in-situ* management) is the cheapest method for harvesting and packing the paddy straw for easy and low cost transportation [13].

There is a huge potential for modern uses of biomass energy in the world particularly in rural India. The modern uses of biomass include conversion technologies such as combustion, pyrolysis, gasification, fermentation and anaerobic digestion for production of heat and electricity, liquid and gaseous transportation fuel, biogas for cooking, composting and mushroom cultivation, building construction, paper product manufacturing, composite material manufacturing, controlling soil erosion, animal feed etc. Out of all these, combustion is still the most widely used process for biomass conversion [14].

Many studies on the design and operation of biomass based combustors, and cook stoves are available for diversified uses. A fluidized bed combustion of rice straw was studied in which straw of bale size 300 × 300 × 300 mm were introduced through chute into 25 m^2 bubbling bed [15].

In a study, of combustor working on fluidized bed principle and using rice husk and rice straw as fuels was tested in which combustion efficiencies were observed from 60% to 80% at bed temperatures from 650 to 850 °C [16]. Inefficient ways with which the biomass is burnt in open three-stone fire and traditional cook-stoves for cooking and heating applications causing severe health problems in women and children and also affects the environment were discussed [17].

The performance of three types of forced draft cook stoves using fuel wood and coconut shell with the aim of reducing fuel wood consumption and pollutants through the use of improved cook stoves considering the important parameters of thermal efficiency and emission levels were studied [18]. A gasifier based cook stove for improving the performance of biomass cook stove was designed in which cotton stalk was used as fuel [19]. In another study, performance of improved biomass cook stove in reducing emissions, eliminating drudgery, and improving overall quality of life was studied using thermal efficiency, cooking duration and specific fuel consumption in comparison with three stone traditional cook stoves [20]. A biomass cook stove was fabricated and analyzed to study the performance based on the principle of forced draft gasifier using single fan for high efficiency in which any solid biomass in the form of pellets can be used in the stove [21].