International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 7, July - 2014

Modelling of Waste Heat Recovery Device for Jaggery Units

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***Abstract*: Production of Jaggery from sugarcane juice is done by evaporating water using large vessels kept over pit furnaces. Bagasse is used as fuel for the process which is obtained by crushing sugarcane. Bagasse has a ready market as biomass fuel that's why improving the efficiency of bagasse utilization to save the bagasse is of interest. Typical values of flue gas temperature in the chimney of commercially operated jaggery units is in the range of 1000-1250K which indicates significant energy losses and hence presents a case for Waste Heat Recovery. Work presented here reports conceptualization, prototype building. Based on modelling results, Waste Heat Recovery device using marble pebble-beds was built at lab-scale. The heat recovered in the beds is used for combustion air-preheating. While packed bed waste heat recovery devices are commercially used in other industries i.e. glass industries, the work presented here proposes the development of concept for the first time for Jaggery units.**

Key Words: Waste Heat Recovery

1. INTRODUCTION

Jaggery is a honey brown coloured condensed form of a sugarcane juice, present in a solid state at room temperature. Jaggery is called as Gur in India, Desi in Pakistan, Jaggery in Burma and African countries, Panela in Mexico and South America, Hakuru in Sri Lanka and NaamTaanOi in Thailand. Jaggery is the traditional sweetening agent used during last few centuries in India [1]. Jaggery processing units are typically operated in decentralized-mode and is a significant agro-based industry. The other raw materials used for jaggery making in India are: Palmyra palm and sweet sorghum. .Figure 1 shows the layout of a typical jaggery making unit. At any point of time, there are about 12-15 workers engaged in various activities such as cane crushing, juice transfer, bagasse drying and charging, juice concentration and monitoring, cooling and moulding of the prepared jiggery. .Jaggery production is a batch process and typically 4-5 batches are completed per day. On an average, the production per batch is about 250 kg of jaggery, which translates into production of about 1 to1.25 tons/day. Jaggery production is a cottage industry and provides a significant employment opportunity for unskilled workers in rural India.

The work reported by Shiralkar et. al. [2] measured flue gas temperatures at chimney-exit to be around 1000-1250 K. This translated into energy losses to the tune of 25-30 % due to hot flue gases exiting through chimney. Sardeshpande et al. [3] reported that a well designed regenerator recovers about 60–65% of total input heat to the regenerator in a glass furnace.

A simple Waste Heat Recovery device with marble-beds for storing-heat, steel pipes carrying hot-flue gas and operated through gate-valves is fabricated at lab-scale. Surveys done earlier clearly indicated that the bagasse saved can be supplied in ready markets to enhance financial sustenance of the sweetener-making units that satisfy needs of large household consumers and some confectionary units.

2. THEORY AND CALCULATIONS

The Waste Heat Recovery device is modelled as a packed bed. The important assumptions made in the analysis are summarized below:

1. One dimensional area averaged model is adequate
2. The packing material (pebbles) can be treated as lumped from a thermal view point (Biot Number < 0.1) and axial diffusion can be neglected.
3. The transient term in the gas energy equation is negligible

The above assumptions lead to a very simplified model. The governing equations are developed for an infinitesimal element of thickness dx at a distance x from the inlet as shown in Fig. 1.

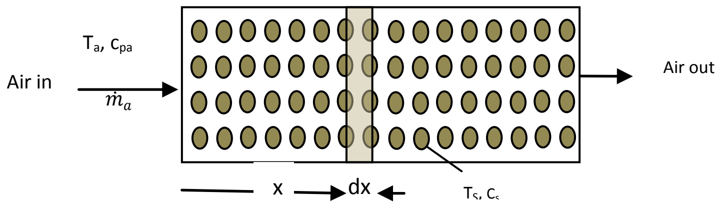

Fig. 1 Schematic representation of the domain of the waste heat recovery device

The energy equation for the pebbles can be written as,

$$M_S' c_S \frac{dT_S(x)}{dt} = h_{air} A_S' (T_a(x) - T_S(x)) \qquad (1)$$

In the above expression M_S' and A_S' are respectively the mass and surface area of the packing material (pebbles) per unit length of the bed. The other parameters involved are, c_S; the specific heat of the pebbles, h_{air} is the heat transfer coefficient; $T_a(x)$ and $T_S(x)$ are the temperatures of the air and the packing material at a distance *x* from the entrance of the bed. The above equation may be rewritten as,

$$\frac{dT_S(x)}{dt} = \frac{h_{air} A_S'}{M_S' c_S}(T_a(x) - T_S(x)) = C_1(T_a(x) - T_S(x)) \qquad (2)$$

Similarly, the energy equation for the air may be written as,

$$\dot{m}_a c_{pa} \frac{dT_a(x)}{dx} = h_{air} A_S' (T_S(x) - T_a(x)) \qquad (3)$$

In the above equation, $\dot{m}_a$ and c_{pa} are the mass flow rate of air and its specific heat at constant pressure respectively. The same equation may be written as,

$$\frac{dT_a(x)}{dx} = \frac{h_{air} A_S'}{\dot{m}_a c_{pa}}(T_S(x) - T_a(x)) = C_2(T_S(x) - T_a(x)) \qquad (4)$$

Equations (2) and (4) are the governing equations for solving the temperatures of the packing and the gas. Once the process conditions and the properties of the bed and bed materials are known, the parameters C_1 and C_2 can be estimated. The applicable initial and boundary conditions are:

$$T_a(t = 0, x) = T_{ambient} \qquad (5)$$

$$T_S(t = 0, x) = T_{ambient} \qquad (6)$$

$$T_a(t, x = 0) = T_{ambient} \text{ or } T_a(t, x = L) = T_{furnace} \qquad (7)$$

It may be observed that the boundary conditions in Eq. (7) will depend on the heating or the cooling cycle. The solution is obtained by the finite difference procedure using first order forward difference. Matlab was used for solving the above set of equations.

3. MATERIALS AND METHODS

3.1 *Apparatus*

Fig.2 shows the schematic diagram of the setup. The packing material to be used in the steel beds will be procured from marble-workers (construction-ancillary units). The piping and beds will be insulated using ceramic-wool to reduce heat losses to the surroundings. Temperatures at appropriate locations will be measured by K-type thermocouples. Air velocity will be measured by Hot-wire anemometer. Dry bagasse will be used as fuel in the furnace.

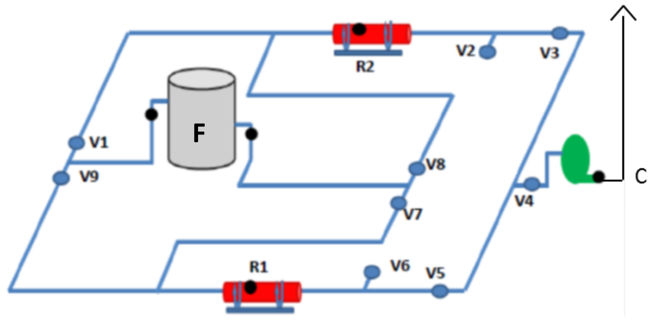

Fig. 2 Schematic of Heat Regeneration Unit

R1 and R2 : Packed beds using marble pebbles;
V1 to V9 : Gate valves;
F : Furnace;
C : Chimney

3.2 *Operating Procedure*

In the first cycle, the flue gas coming out of furnace passes through the bed R1and fresh air from the open valve V1, enters through the bed R2. Packing material (i.e. Marble pebbles) will capture the heat from the flue gas. The flue gas then exits *via* blower through chimney. When the temperature of the flue gas drops to 200°C, the flow is reversed and then flue gas is directed through the bed R2 while ambient air is passed through the bed R1. This air gets heated using pebble-heat stored in R1 and is sent to the furnace as preheated combustion air. The time required for passing flue gas from one bed has been computed to be 11 minutes as described in section 2. The quantity of water taken for experiment is 30 liter. The theoretical total amount of bagasse required assuming 100 % combustion is 4.84 kg. Table 3 gives comparison of pressure drop and heat transfer coefficient values for various pebble diameters. It is clear that as pebble diameter increases, the heat transfer coefficient decreases and bed pressure drop also decreases. Three cm pebbles were selected as they offer reasonably good heat transfer coefficient as well as low pressure drop.

4. RESULTS

4.1 *Simulation results*

From the simulation results, the proposed dimensions of Regenerator (Bed) are as follows: Length of bed=0.5 m; Cross-sectional area of bed= 0.008 m^2; Diameter of bed= 10.12 cm; Diameter of balls=0.03 m; Number of pebbles = 180.

The simulated temperature profiles along the bed length under different conditions are shown in Fig.3. Table 1 shows that, with increase in the length of bed the bed pressure drop increases but the exit gas temperature decreases. As the desired exit gas temperature is 200°C, the bed length of 0.5 m was selected for our experiments. The simulation results in Table 2 indicate that as gas velocity increases, the parameters such as heat transfer coefficient, bed pressure drop and exit gas temperature increases. However, the desired exit gas temperature is 200°C. The flue gas velocity of 1.2 m/s gave temperature close to the desired.

Table 1 Effect of length of bed on temperature and other parameters

Length(m)	0.4	0.5	0.6	0.7
Surface area (m^2)	0.4072	0.5089	0.6079	0.7096
Heat transfer coefficient (W/m^2°c)	71.63	71.63	71.63	71.63
Gas temperature (T_g in °c)	283.35	201.22	133.69	85.28
Solid temperature (T_s in °c)	178.05	128.66	88.21	60.13
Combustion air temperature (T_a in °c)	223.46	256.48	276.52	289.57
Solid temperature (T_s1 in °c)	230.05	273.89	301.90	320.81
T_g1(°c)	283.50	201.37	133.82	85.37
T_s2(°c)	265.25	193.25	130.50	84.18
Pressure drop (N/m^2)	173.60	217	260.4	303.80

Table 2 Effect of gas velocity on temperature and other parameters (length: 0.5m)

Gas Velocity(m/sec)	0.5	1	1.2	1.5
Cross section area of bed(m^2)	0.0193	0.00967	0.008058	0.006447
Surface area of bed (m^2)	1.2158	0.6079	0.5089	0.4072
Heat transfer coefficient (W/m^2K)	39.90	63.38	71.63	83.13
Gas temperature (T_g in °c)	70.89	163.42	201.22	255.44
Solid temperature (T_s in °c)	46.01	101.11	128.66	172.19
Combustion air temperature (T_a in °c)	216.16	251.50	256.48	256.45
Solid temperature (T_s1 in °c)	180.48	256.49	273.89	288.33
T_g1 (°c)	70.94	163.54	201.37	255.62
T_s2 (°c)	63.56	154.49	193.25	249.07
Pressure drop (N/m^2)	43.09	153.85	217	332

Table 3 Effect of pebble diameter on pressure drop and heat transfer coefficient

Pebble diameter(m)	0.01	0.02	0.03
NRe_m	156.80	313.6	470.30
Surface area of bed (m^2)	1.5227	0.7615	0.5089
Heat transfer coefficient (W/m^2K)	102.84	81.82	71.63
ΔP(N/m^2)	785	342.28	217

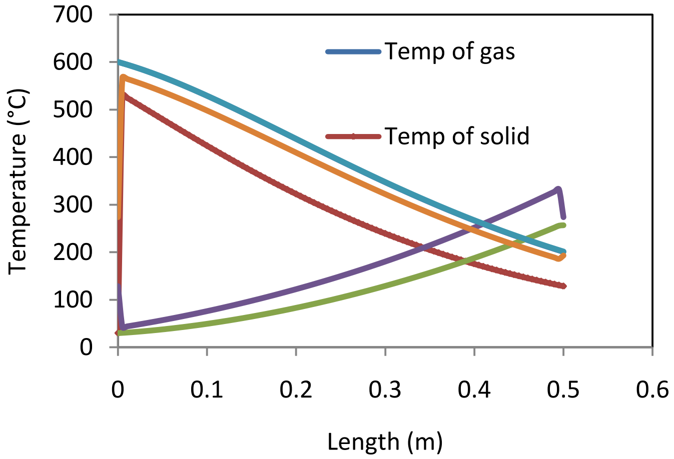

Fig.3 Temperature profiles of gas, air and solid along the bed height in two consecutive cycles

5. CONCLUSION

The dynamic simulations of Waste Heat Recovery device, incorporating randomly packed bed of marble pebbles, provide with the detailed information of the temperature distribution inside the bed as well as the temperature of the flue gas. Model results were used for designing and constructing a lab-scale Waste Heat Recovery device. Unit designed in the present work is capable of recovering substantial waste heat from the flue gas.

6. REFERENCES

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