Global Journal of Engineering and Technology Advances

eISSN: 2582-5003

Cross Ref DOI: 10.30574/gjeta

Journal homepage: https://gjeta.com/

(RESEARCH ARTICLE)

Microcontroller based logic control system for automated novel paddy straw bale combustor technology applied to greenhouse heating

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Global Journal of Engineering and Technology Advances, 2023, 14(02), 030–042

Publication history: Received on 01 December 2022; revised on 12 January 2023; accepted on 15 January 2023

Article DOI: https://doi.org/10.30574/gjeta.2023.14.2.0014

Abstract

Automation of paddy straw bale combustor technology was achieved by designing a microcontroller based logic control system for controlling bale feeding, ensuring complete combustion of paddy straw bale and cleaning of the grate by removing bottom ash. The system generates flue gas at 350 °C to maintain greenhouse air temperature 10 °C higher (for 24 h continuous operation) than ambient air during winter months for Ludhiana climate (30.56 °N), India. The microcontroller controls the automatic opening of the furnace door, conveyor speed for forward bale speed by motorized operation of chain and sprocket mechanism attached to the door, door closing and opening for specified time, grate shaker with comber driven by 0.5 hp motor actuated by microcontroller and operated by a worm gear.A microcontroller controlled panel was designed with six preset values of small amount of fuel delivery by each injector onto the bale for complete combustion. The resonant circuit was provided with the help of a crystal, X1 10 Mhz and C4, C5 capacitors to get accurate timing calculations in each operation in milliseconds as used in the circuit. The compatible microcontroller used for the purpose was AT89C2051 as it matched with the desired operational parameters at low cost. It was observed that the developed microcontroller based logic control system could achieve the desired operations of bale feeding, fuel injection and grate cleaning at >98% efficiency.

Keywords: AT89C2051 Microcontroller; Automatic bale combustor; Bale feeding; Greenhouse heating; Flue gas

1. Introduction

A small computer on a single metal oxide semiconductor (MOS)integrated circuit (IC) chip is basically called a microcontroller. Discrete chips are designed in a microcontroller and embedded for specific applications.There are number of automatic applications in industry, medical devices, engine controls, power tools remote controls where microcontrollers are used. Microcontroller helps in reducing the size and cost of the product thus making it economical for digital control of processes and devices. Considering the current scenario of the internet of things, use of microcontrollers have become a popular and economical means of data collection, sensing and actuating the mechanical technologies for smooth and continuous functioning of any process [1]. Currently the microcontrollers are being used in several important applications for improving the efficiency and smoothness in operations such as; greenhouse microclimate control, renewable energy systems (solar tracking devices, biomass systems, and photovoltaic systems), automation and precision agriculture, thermo electric and refrigeration systems, industrial and agricultural automation processes. A few of such important studies are presented here.A time delay system was used in a microcontroller design and control implementation for a greenhouse application [2]. By altering the controller set points and data based integration, greenhouse environmental demand for various plant species were considered through a batch control system during start and operation run by means of a discrete control algorithm running in the background.

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An 80C32 microcontroller operating a meteorological 10 sensor data-acquisition system which could be programmed between one minute to one hour was designed and tested to supervise the growth of bananas in a greenhouse in a remote area [3]. The operation of was found to be successful as banana production was observed near to optimum value at higher relative humidity and temperature varying around 25°C inside the greenhouse. Thermoelectric (TE) devices at different temperatures were used in which direct conversion of heat energy to electricity for battery charging operation was attempted [4] with the objective of designing a TE operated battery charger using waste heat or alternate heat source as direct power input. MPPT feature was used on a dc-dc converter and controlled by a microcontroller. The designed system produced 15% better charging as compared to conventional system.

An electrical energy management system for renewable energy applications was developed [5] using a microcontroller (AT89C2051, ADE7757) and solar power system. The system was equipped with smart energy metering system with independent distribution, controlling and monitoring sub-system generating and equal amount of electrical energy as per requirement. The system was also controlled by an alternative source of electricity using solar energy that used a 10–40 W solar panel for 10A load using the designed microcontroller. Weed population in field crop was controlled by an herbicide applicator by coupling with a manually operated three row roller contact type microcontroller [6]. The control system provided the quantified weed information of the herbicide application to a microcontroller through a relay and a dc solenoid valve for variable rate application of herbicide. MATLAB software captured the image and analyzed using the image processing toolbox.

The quantity of herbicide to be released is controlled by the microcontroller which was activated by the solenoid valve using a relay as per the decision algorithm prepared for the purpose. Use of the designed machine tool in experimental studies showed an average of 50% saving of herbicide at weeding efficiency of 90%. A microcontroller attached to a solar tracker with a hybrid algorithm controlled it by both sensors and mathematical models to determine the exact position of the sun for optimal utilization of solar energy [7]. Hybrid solar tracking system results revealed that generated solar power was consistently higher as compared with the experimental results. A bidirectional buck–boost converter for photo-voltaic power plant was operated through a microcontroller 8051 and simulations performed using Psim for complete design of the converter. Accurate working of converter in buck mode and boost mode using microcontroller was observed [8]. Microcontroller based system was used to run automatic room heater control and simulation run was performed using Proteus 8, circuit building software used for building electronics system. The results were satisfactory as per design specifications [9].

A closed loop control system for continuous compaction of large square baler was developed by using different bale densification method through auger and conical compaction rollers using a microcontroller based system [10]). Fifteen-times reduction in force was achieved as compared to plunger type conventional system with bale densities ranged from 166 to 334 kg·m^{-3} (dry basis) and applied auger forces less than 44 kN. A microcontroller-based embedded system was presented for an automatic slip-draft control for a 2WD tractor [11]. The tractive performance during ploughing and harrowing were improved by 9.17% and 6.05% as compared to existing draft control system. An automation of drip irrigation was presented using a microcontroller through GSM module [12]. As soon as the message is received on farmer's mobile phone about the field wetness status microcontroller activates the irrigation (if required) through logic control system. Three month testing of the system on paddy field revealedthat about 41.5% and 13% of water savings could be achieved compared to the conventional flood and drip irrigation methods respectively.

A machine vision approach for tomato grading and sorting was developed using a microcontroller [13]in which grading of tomatoes in three stages with digital images were captured. Four performance parameters; the accuracy, specificity, sensitivity and precision metrics were used under three grading stages for communication with the microcontroller to enable the respective motor for proper fruit selection and collection in the respective bin.Arduino microcontroller was used in a novel low coast flow control system in absorption chillers using the LiBr/H_2O pair for gauging, controlling flow and maintaining optimal operating conditions [14]). The presented system worked well and produced 0.60 L/min flow rates for 67% of the flow range provided by the conventional magnetic centrifugal pump recirculation system. Remote monitoring function for round baler was used to develop a sensor based control system [15]). Using the remote monitoring terminal RS232 from the controller, working efficiency of automatic feeding net increased by 14.91% as compared with the annual net feeding. Light to frequency converter principle using PILOT-PANEL scheme was applied on a dual solar tracking system using microcontroller support [16].The changes due to altitude angle of the sun were incorporated within the microcontroller program to move the tracking system between four and eight time a year in steps of about 9° for maximum solar radiation collection of 98.36% with continuous tracking and minimum energy consumption as compared to the previous studies where the harvested energy was nearly 85%.

Handling of abundantly available paddy straw particularly in baled form for productive and efficient use has been a major bottle neck in the developing countries where due to non-availability of any efficient paddy straw burning technology for useful heating applications farmers has to burn the straw in the open fields in order to clear the field for sowing of next crop. Open field burning cause environmental pollution and also affects human and soil health. In order to resolve this problem, forced draft paddy straw bale combustor technology was developed for feeding and combustion of bales to generate flue gas for useful heating applications [17]. However, due to non-automated components, it was difficult to operate it smoothly and lot of labour and human effort was involved.

In this study, automation of the important components of forced draft paddy straw bale combustor technology is presented using a microcontroller based logic control system.The main objective of this study is to design, develop and test amicrocontroller based logic control system to tackle the major problems of controlled feeding, complete burning of paddy straw bales (of about 20 kg weight each) and bottom ash removal from the grate through the automatic operation of opening and closing of furnace door for already loaded bales (12 in a row) on a conveyor and roller arrangement one after the other and move forward for hassle free operation of generating the hot flue gas above 350°C and hot water above 65°C in order to maintain the greenhouse air temperature about 10°C higher than the ambient air during winter nights to improve the crop productivity. The developed secondary microcontroller allows the automatic operation of solenoid valve controlled fuel injector to spray an optimized amount of fuel for smooth and complete combustion of the bale. The final automatic operation handled by the microcontroller is the operation of grate shaker with combing operation to automatically clean the grate beneath the burnt biomass i.e. the bottom ash. The developed microcontroller based logic board system allows the smooth operation of various components of the automatic bale combustor (ABC) technology developed for greenhouse heating with the desired operational parameters at low cost. Moreover, no such study involving microcontroller based operations for paddy straw bale combustor technology were located in the literature.

2. Material and methods

2.1. Mechanical design details of automated bale combustor (ABC) technology

The developed ABC technology is a combination of number of working parts and operations, the details of this technology were published [17]. It was reported that the average time taken for complete combustion of 20 kg bale was 36 min. Therefore, automatic furnace door opening and the conveyor movement for feeding of the next bale was programmed appropriately using a microcontroller to avoid any gap in bale feeding for continuous combustion operation. It is pertinent to note that due to the design and operation of solenoid valve operated pilot fuel injection system, the flame sustainability of the bale was properly achieved and the bales were smoothly burnt one after the other thereby maintaining almost steady state operating conditions generating flue gas at around 350°C for long hours of ABC operation. Mechanical component details of the ABC technology were already published [17].

2.2. Design of microcontroller based bale feeding system and grate shaker with comber

Paddy straw bale feeding mechanism consists of a MS frame with roller and conveyor arrangement, about 10 m long and 1.8 m wide. The cylinder close to the furnace is rotated at a speed of 4 rpm by a chain and sprocket mechanism with a speed reduction of 1.22, driven by a 1 hp motor. 10 to 12 bales of size 94cm×78cm×48cm in size each weighing about 20 kg were placed on the conveyor in one loading for 7 h of continuous operation (Fig. 1a pictorial view and Fig. 1b Isometric view). In order to automatically feed one bale inside the furnace in 5 sec, the optimum forward movement was calculated as 10.6 cm s^{-1}. The whole cycle was optimized in such a way that after 2135 sec the door starts opening automatically. The operation is programmed for 10 sec for the furnace door to open which remains open for 10 sec during which the conveyor moves forward for 5 sec to feed the next bale and the door again closes in 10 sec to make it 2160 sec or 36 min (Fig. 2a pictorial view and Fig. 2b Isometric view). The whole operation was made automatic (controlled by microcontroller) for smooth feeding of bales one after the other without any monitoring or manual operation for the whole night.It is pertinent to note that bale slides through a 45° inclined MS fixed sheet platform attached to the conveyor system and fitted at the mouth of the furnace facing the door.

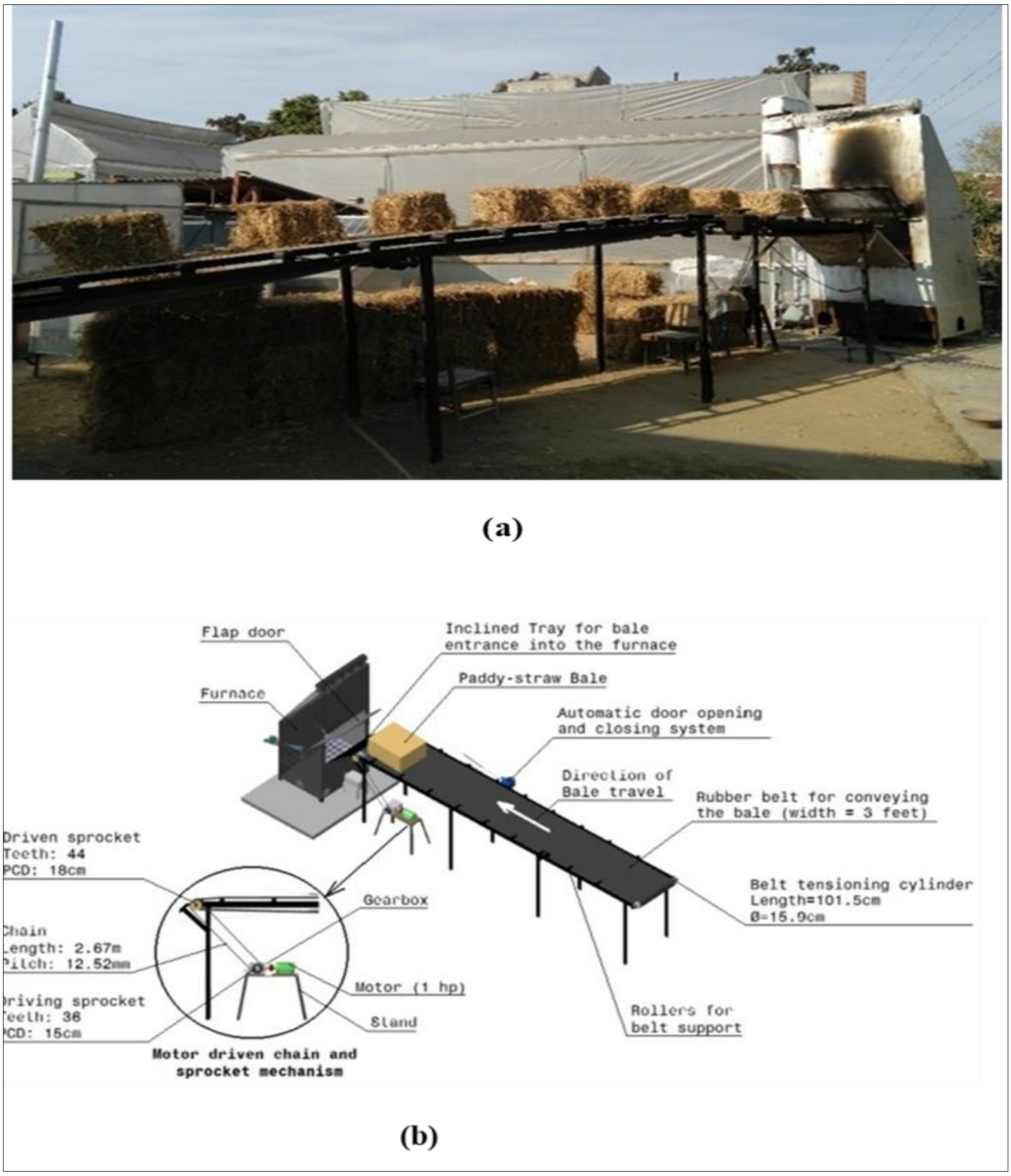

Figure 1(a) Pictorial and (b) Solid model isometric view of the automatic bale feeding system

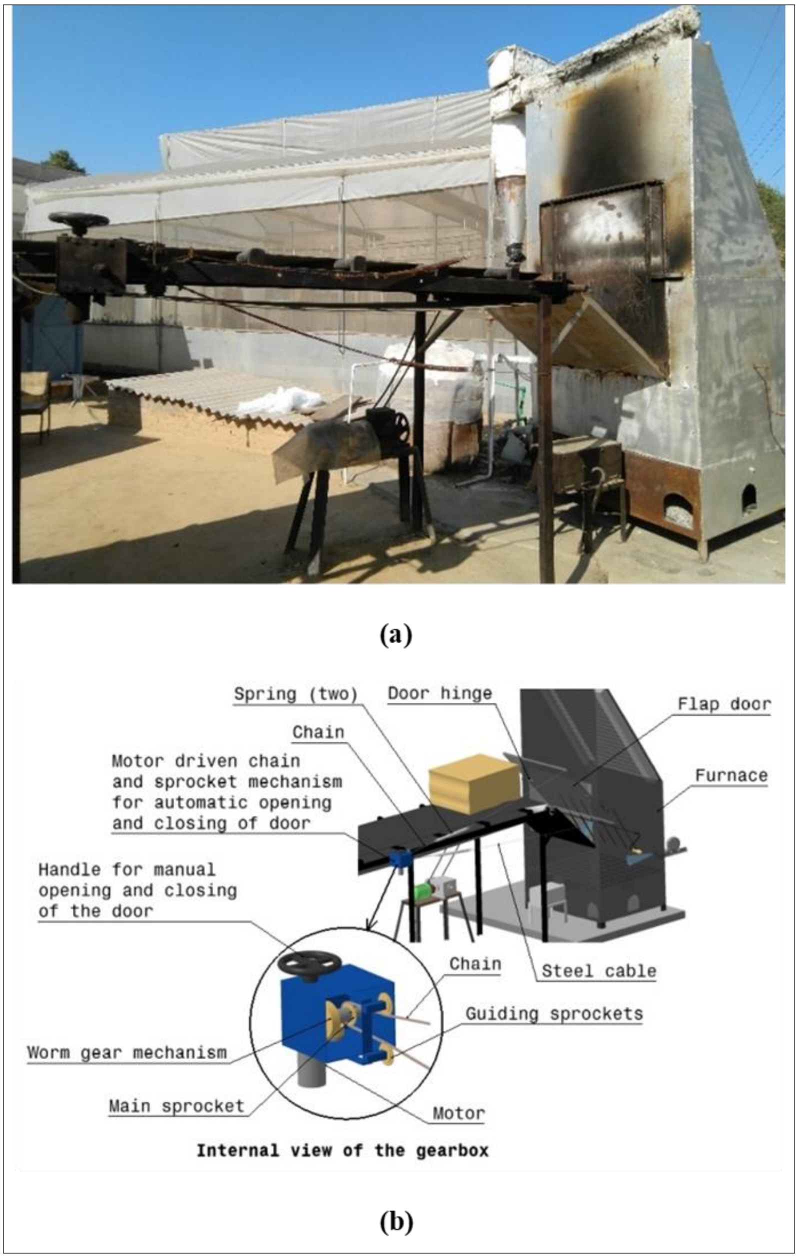

Figure 2 (a) Pictorial and (b) Solid model isometric view of the automatic door opening and closing mechanism

3. Theoretical design

3.1. Automatic bale feeding system

The chain used in the mechanism was an ISO series 08B chain with a pitch of 12.52 mm. The required length of the chain (L) was calculated using the Eq. 1 that comes out to be 2.67 m. A driving sprocket with 36 teeth and a driven sprocket with 44 teeth were selected having a pitch circle diameter of 15 cm and 18 cm respectively that corresponded to a speed reduction of 1.22.

$$L = Kp \text{ ……………(1)}$$

The number of links in the chain was calculated as 213 using the Eq. 2 (Gupta and Khurmi 2009 [18]).

$$K = \frac{T_1+T_2}{2} + \frac{2x}{p} + \left[\frac{T_2-T_1}{2\pi}\right]^2 \frac{p}{x} \qquad \text{……………(2)}$$

The rpm (N) of the driven sprocket was calculated using Eq. 3.

$$v = \frac{\pi D N}{60} \text{ ……………..(3)}$$

A reciprocating motion comber (135 cm × 100 cm) having 120 (12 × 10) nails of 10cm height, at a spacing of 11.5 cm and coupled with 0.5 hp motor and worm gear mechanism was also designed for automatic removal of bottom ash from the grate (Fig. 3a pictorial views and Fig. 3b as isometric view). The worm attached to the motor shaft meshes with a worm wheel and transmits rotary motion at right angle with a speed reduction of 48. This rotary motion is then converted to reciprocating motion of the comber using a slider-crank mechanism. The reciprocating motion of 7.68 cm between the grate bars helps in removing the bottom ash from the grate to the lower sump thereby keeping the grate clean for fresh air supply and complete combustion of the subsequent bales. This component automatically operates for 15 sec after every 15 minutes of combustor run in order to remove the fly ash from the grate (controlled by microcontroller).

Figure 3a Grate shaker with worm gear and slider crank arrangement and comber

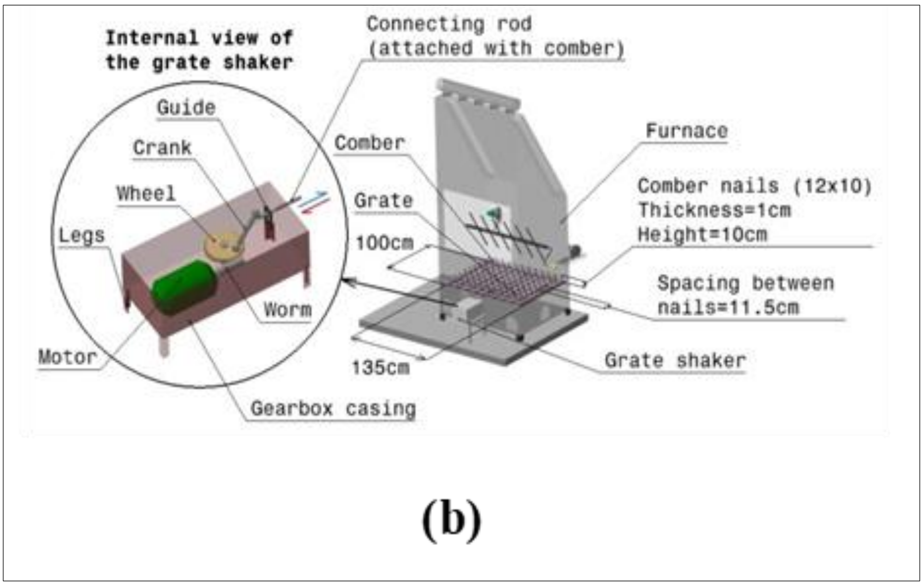

Figure 3b Solid model isometric view of the grate shaker with comber mechanism

3.2. Worm gear mechanism

A 0.5 hp motor having 1440 rpm was used for the motion of grate shaker. A single start thread worm having a pressure angle of 14.5° was used. The torque (M_t) acting on the worm (or worm wheel) was calculated using Eq. 4 (Gupta and Khurmi 2009 [18]).

$$P = M_t \omega \text{.............}(4)$$

The rotational speed of the motor is related to rpm (N) of the motor as per Eq. 5.

$$\omega = \frac{2\pi N}{60} \text{.............}(5)$$

The tangential force $(P_1)_t$ acting on the worm is then calculated using Eq. 6 (Gupta and Khurmi 2009 [18]).

$$(P_1)_t = \frac{2M_t}{d_1} \quad \text{................}(6)$$

The axial force $(P_1)_a$ acting on the worm is calculated using Eq. 7 (Gupta and Khurmi 2009 [34]).

$$(P_1)_a = (P_1)_t \left(\frac{cos\alpha cos\gamma - \mu sin\gamma}{cos\alpha sin\gamma + \mu cos\gamma}\right) \text{..................}(7)$$

The lead angle γ is calculated using Eq. 8 (Gupta and Khurmi 2009 [18]).

$$tan\gamma = \frac{l}{\pi d_1} \quad \text{.............}(8)$$

The radial force $(P_1)_r$ acting on the worm is calculated using the Eq. 9 (Gupta and Khurmi 2009 [18]).

$$(P_1)_r = (P_1)_t \left(\frac{sin\alpha}{cos\alpha sin\gamma + \mu cos\gamma}\right) \text{.............}(9)$$

The axial, radial and tangential components of force acting on the worm and worm wheel are related to each other according to the Eqs. 10, 11 and 12.

$$(P_2)_t = (P_1)_a \quad \text{...............}(10)$$

$$(P_2)_a = (P_1)_t \quad \text{...............}(11)$$

$$(P_2)_r = (P_1)_r \quad \text{.................}(12)$$

Where, subscripts 1, 2 corresponds to worm and worm wheel respectively and subscripts a, t and r corresponds to axial, radial and tangential components respectively.

The tangential, axial and radial components of force acting on the worm were calculated to be 160.26N, 855.3N and 223N respectively.

3.3. Microcontroller design for bale feeding and grate shaker operation

The heart of the logic control board is microcontroller performing all the functions of the automated bale combustor (ABC) technology as shown in Fig. 4.

After power up, the microcontroller continuously pooling push button switch (Start Switch) on port 1.3 and if this switch is low for more than 20 ms the following sequence will be activate. Drum starts reciprocating and rotary motion for 10 second and stops through Port 1.7, U1:E, R12, Q5 and finally RL5.Grate shaker starts for 10 second and stops through Port1.4, U1:B, R3, Q2, and RL2. Door opening starts for 10 second and stops through Port 1.0, U1: C, R2, Q1, RL1 and hold the state of opened door. The Conveyor starts moving carrying the equally spaced bales to the combustor for 5 second and drop the ball intothe firing pit of the furnace and stops through Port 1.2, U1:A, R4,Q3 and RL3.Door closing starts for 10 second and stops through Port 1.1, U1: C, R2, Q1, RL1 and hold the state of closed Door.

The action is repeated from beginning after 2160 second because during operation burning time of given bale is 2135 second (5 + 10 + 10 sec are for conveyor movement, door opening and closing respectively). The system is programmed for 40 bales of 20 kg each for 24 hr continuous operation (36 min for each bale burning time) and then stops or needs to be restart.The burning of bale starts and the role of other microcontroller starts to inject fuel to bales as per 6 selector switch settings as follows through Port3.7, R6 and Q1.

The power supply after step down to 12 V through transformer goes to J1 and J2 and BR1 converts the AC supply to DC supply and smoothening capacitor C3. 3 terminal voltage regulator (U3) regulates the voltage to 5 V for entire circuit operation. The LED indicator D5 in series with resistance R6 shows the presence of 5V power.The power supply after step down to 24 V through transformer goes to J3 and J4 and BR2 converts the AC supply to DC supply smoothed out through C2 capacitor to drive the relays RL1 to RL5. The LED indicator D12 in series with resistance R7 shows the presence of 24V power.

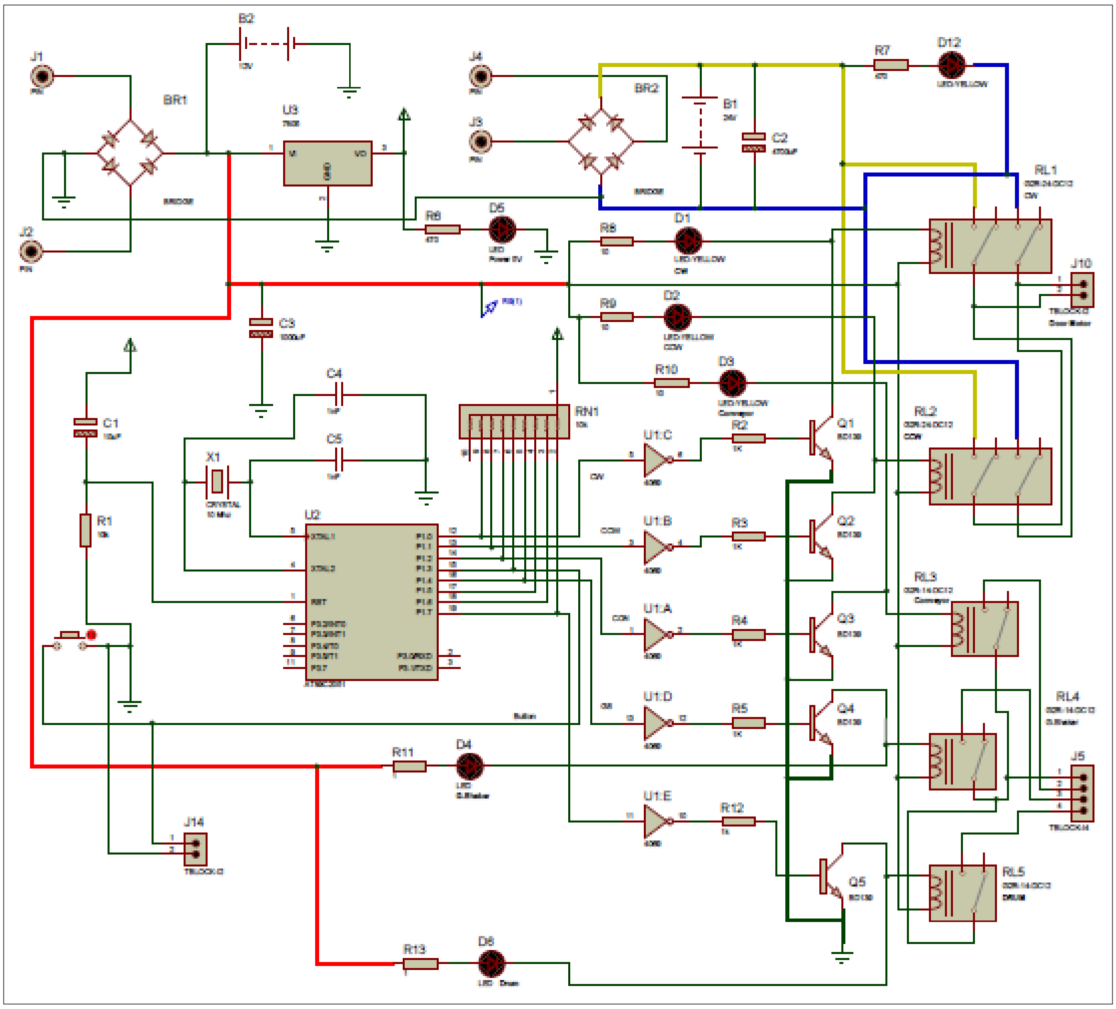

Figure 4 Schematic circuit diagram of microcontroller based logic control board the operation of ABC technology

The resonant circuit is provided with the help of a crystal, X1 10 Mhz and C4, C5 capacitors to get accurate timing calculations in each operation in milliseconds as used in the circuit. The power on reset of micro controller is provided by R1 and C1 RC (Resistance-capacitor) delay network. RN1 is a pull up resistance network provided for port 1 of micro controller for logically making the pins at positive potential (high). The compatible micro controller used for the purpose is AT89C2051 as it matches with the desired operational parameters at low cost. Port 1.0, P 1.1, P 1.2, P 1.4 and P 1.7 are output ports. P 1.3 is input port.Port 1.0 drives a logical inverter gate U1:C which drives the relay RL1 through transistor Q1 and resistor R2, thereby door opening operation is accomplished by a DC motor mounted on the side of conveyor belt frame.Port 1.1 drives a logical inverter gate U1:B which drives the relay RL2 through transistor Q2 and resistor R3, thereby door closing operation is accomplished by a DC motor mounted on the side of conveyor belt frame.Port 1.2 drives a logical inverter gate U1:A which drives the relay RL3 through transistor Q3 and resistor R4, thereby conveyor belt operation through a geared motor and VFD (variable frequency drive) is accomplished by 3 phase induction motor (1hp) mounted on the side of conveyor belt frame. Port 1.4 drives a logical inverter gate U1:D which drives the relay RL4 through transistor Q4 and resistor R5, thereby operation of grate shaker through a worm gear and slider crank mechanism is accomplished by 3 phase induction motor (0.5 hp) foot mounted on front side of the furnace. Port 1.7 drives a logical inverter gate U1:E which drives the relay RL5 through transistor Q5 and resistor R12, thereby operation of rotary and reciprocating drum motion is accomplished by 3 phase induction motor (0.5hp) foot mounted near the side wall of the furnace. Port 1.3 is always logically high (5V) while a start push button is pressed to activate or initialize all the systems, it goes low (V = 0) and the operation starts.

LEDs D1, D2, D3, D4 and D6 are to indicate the operations of 5 operations which are controlled through micro controller. D1 indicates the door opening, D2, Door closing, D3 conveyor, D4 grate shaker and D6 the drum movement. B2, B1, J10, J5, J14 were used for trial of demo board in the form of simulations.

3.4. Microcontroller design for fuel injection system

After step down AC voltage to 12 Volts BR1 (bridge rectifier) and C1 (smoothing capacitor) converts it to DC 12 V and U1 as shown in Fig. 5.

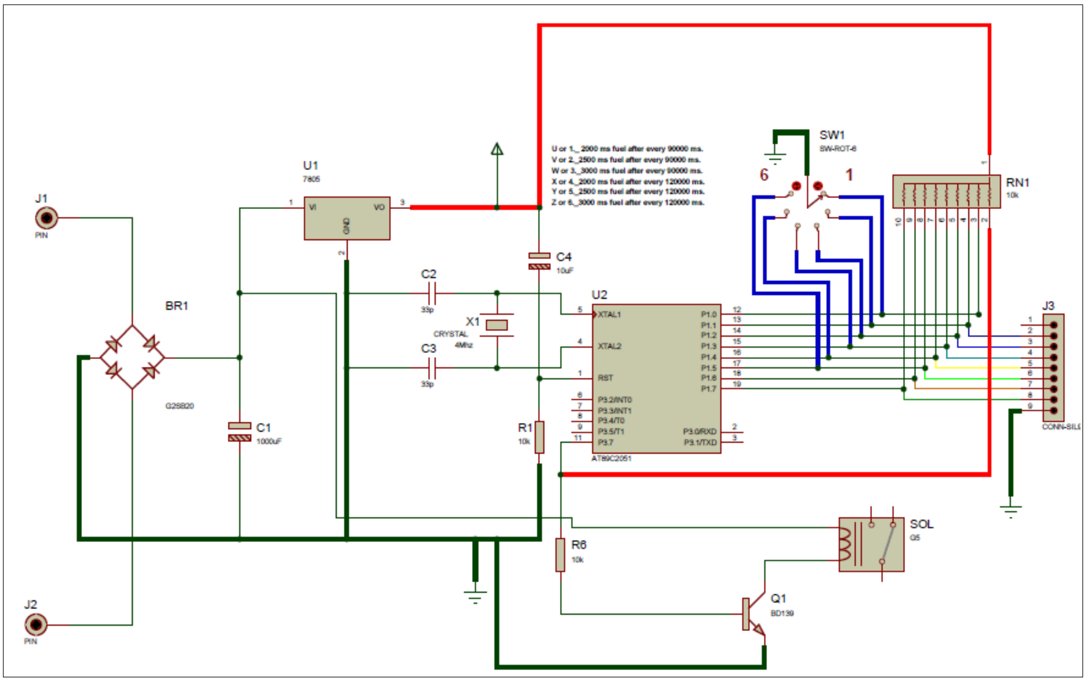

Figure 5 Schematic circuit diagram of microcontroller based logic control board for the automatic operation of Fuel injector

Three terminal voltage regulator regulates the voltage to drive the circuit. Power on reset of micro controller is performed with C4 and R1. The resonant circuit is provided with the help of a crystal, X1 10 Mhz and C2 and C3 capacitors to get accurate timing calculations in each operation in milliseconds as used in the circuit. Port 1 is an input port pulled up with the help of network resistor RN1. J3 is connector used for trial of demo board. Port 3.7 is an output port and drives solenoid valves of injector through Q1 and R6. Different timing periods for injecting fuel are; 2000 milliliter fuel after every 90000 millisecond (port 1.0), 2500 milliliter fuel after every 90000 ms (port 1.1), 3000 milliliter fuel after every 90000 ms (port 1.2), 2000 milliliter fuel after every 120000 ms (port 1.3), 2500 milliliter fuel after every 120000 ms (port 1.4), 3000 milliliter fuel after every 120000 ms (port 1.5).

Time for actuation of furnace door opening, closing, stay open/close position, bale movement and dropping inside the furnace time were matched with the microcontroller based settings with the help of a digital stopwatch.

4. Results and discussion

Twelve bales were loaded on the conveyor and equally placed at specified distance as per optimum forward speed of the conveyor belt (Fig. 1). The microcontroller actuated the conveyor movement (forward speed) through the motor and gear mechanism and fed each bale exactly after 36 min starting 20:00 hrs (Table 2 column 3).

The performance of the microcontroller operated logic control system was observed in terms of automatic bale feeding after every 36 min time interval. It is important to note that when small part of the bale was left unburnt, the flue gas temperature started to drop a bit indicating the need for next bale feeding to the combustor after 36 min of burning. The designed microcontroller handled this aspect perfectly and actuated the conveyor at exact time. All the bales were correctly fed inside the furnace except two bales (at 21:48 and 00:48 hrs) when due to human error the bale stuck at the door but was immediately corrected and allowed to fall in the furnace pit manually. Hence, the performance of automated bale feeding system was almost 100% as shown in Table 2.

Fuel tank was filled with 1 litre diesel at the start of the trial. Microcontroller based preset condition of 2 ml diesel spray after every 2 min by each pump was used for complete combustion and optimum flue gas temperature. The fuel injection was noted at the end of the experiment and the total fuel consumed in 7 hr operation was calculated (2 × 30 × 7 = 420 ml) which was very close to the measured amount of 570 ml. The rest 430 ml were consumed. The excess 10 ml consumption may be due to evaporation of the fuel in the tank and during spray. The 98 % accuracy was observed for the microcontroller based fuel injection preset conditions that controlled the automatic spray of fuel onto the bale for complete combustion.

Bottom ash removal in kg was measured to test the performance of the microcontroller based grate shaker and drum type comber mechanism. The literature studies show that under complete combustion conditions of paddy straw about 17.23% ash content is left which means for a 20 kg bale, ideally 3.44 kg of ash is produced inside the furnace grate and needs to be removed frequently for proper combustion and continuous operation. After the complete combustion of 1st bale, bottom ash removed by grate shaker and comber as actuated by microcontroller at the specified time of 10 sec after every 10 min. The bottom ash removed after each bale feeding is shown in Table 2 column 5. It was observed that it remained between 3.18 kg to 3.35 kg during the trial period. The total collection for 7 h operation was 39.26 kg for 12 bales. Ideally it should have been 41.35 kg but as the flue gas air movement from the bottom of the grate cause some fly ash to leave the furnace along with the flue gas which was then collected at the gravity setting chamber and wet scrubber to allow clean exhaust through the chimney.Hence the sum of the weight of bottom ash below the grate and the fly ash collected becomes very close to the ideal value of 41 kg that authenticates the performance of micro controller actuated grate shaker and comber operation of 10 sec movement after every 15 min at 2 ml fuel supply after every 2min is found to be more than 98% accuracy in operation.

Table 2 Effect of microcontroller based logic control system on flue gas temperature rise, bale feeding status and bottom ash removal

Time of the day (hrs) (1)	Flue gas temperature (°C) (2)	Time of next bale feeding (hrs) (3)	Bale feeding status (4)	Bottom ash removal (kg) (5)
20:00	109.3	20:00	Correctly fed	
20:15	162.5			
20:30	156.4			
		20:36	Correctly fed	3.32
20:45	185.6			
21:00	200.4			
		21:12	Correctly fed	3.28
21:15	210.8			
21:30	236.4			
21:45	228.8			
		21:48	Not correctly fed	3.35

			(Bale was diagonally placed)	
22:00	290.4			
22:15	310.5			
		22:24	Correctly fed	3.30
22:30	330.6			
22:45	352.8			
23:00	344.6	23:00	Correctly fed	3.26
23:15	355.4			
23:30	351.3			
		23:36	Correctly fed	3.28
23:45	358.4			
00:00	360.6			
		00:12	Correctly fed	3.30
00:15	350.4			
00:30	358.6			
00:45	352.3			
		00:48	Not correctly fed (Loose straw stuck in the door side)	3.32
01:00	357.4			
01:15	361.6			
		01:24	Correctly fed	3.25
01:30	357.2			
01:45	350.6			
02:00	348.4	02:00	Correctly fed	3.22
02:15	356.4			
02:30	352.8			
		02:36	Correctly fed	3.20
02:45	360.5			
03:00	352.7			
		03:12		3.18

Nomenclature

d_1= pitch circle diameter of the worm (m)
D = Diameter of the cylinder including belt thickness (m)
K = no. of links in the chain
l = lead of the worm (mm)
N= Rotational speed (rpm)
p = pitch of the chain (mm)
P=Power of the motor (W)
T_1 = number of teeth on the driving sprocket
T_2 = number of teeth on the driven sprocket

v = peripheral speed of the cylinder (m/s)
x = distance between the centres of the two sprockets (mm)
ω = rotational speed of the motor (rad s^{-1})
α= pressure angle (°)
μ = coefficient of friction
γ = lead angle (°)

5. Conclusion

The designed microcontroller based logic control system for automated operations of novel bale combustor technology was fully able to generate flue gas above 350 °C due to which 10°C higher greenhouse air temperature could be maintained for dayand night continuous operation. The mechanical and microcontroller based electronic designs for the operation of controlled bale feeding, complete combustion of paddy straw bale and cleaning of the grate by removing bottom ash were tackled successfully in the trial run of 12 bales. Mechanical designcomputations of forward speed of conveyor, door opening and closing using chain and sprocket mechanism, and reciprocatory motion of comber using worm gear and slider crank mechanism calculated through relevant equations matched well with the automatic performance with almost 100% perfection. Microcontroller based intermittent fuel (diesel) supply at present value was fully achieved through a solenoid valve operated fuel injector for flame sustainability and complete combustion of paddy straw bales. The AT89C2051 microcontroller used for the purpose was fully compatible as it matched with the desired operational parameters at low cost. Finally, it can be concluded that the developed microcontroller based logic control system could achieve the desired operations at >98% efficiency.

Compliance with ethical standards

Acknowledgments

The authors are greatly thankful to the authorities of Punjab Agricultural University, Ludhiana and Indian Council of Agricultural Research, New Delhi, India for providing financial aid and necessary facilities for the successful completion of the study. The authors are also thankful to M/s Citizen Electronics, Nawanshehr, India for helping in the development of microcontroller based logic control system for the automation of the developed technology.

Disclosure of conflict of interest

It is declared that the research paper entitled "Design and evaluation of novel paddy straw bale combustor technology for automatic operation using microcontroller based logic control system for greenhouse heating" authored by V P Sethi, Ashwani Sharma, Sumit Chopra has no clash of interest with any person or organization and is a bonafide study carried out in the Department of Mechanical Engineering, Punjab Agricultural University, Ludhiana, India.

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