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DEVELOPMENT OF APPLICATION TAILORED LOW-COST STEAM GENERATOR FOR GASIFICATION PROCESS

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Abstract: The gasification process is considered as the centre of clean coal technology. Several types of gasifying reactants can be used in the gasification process. Amongst them, using steam is recommended for the high concentration of hydrogen in the synthesis gas. Commercially available steam generators are readily available to purchase in the market. However, their cost and accessibility are the main disadvantages for use in tailored research applications as laboratory scale gasification. In this paper, the development and setting up of a steam generator will be presented, with the mass flow ratecontrolled by a microcontroller. The total power of the steam generator is 1800 W, and the mass flow rate is adjustable between 1 and 20 g/min. The produced steam can be supplied by the steam generator at a high temperature of 300 °C continuosly during the experiment. The main advantage of this steam generator is the cost/value of the tailored setup that could also be easily connected to the main PLC controller of the gasifier.

Keywords: steam-generator, thermochemical processes, coal gasification, synthesis gas

INTRODUCTION

In 2019, more than 60% of the electricity generation in the world is produced from fossil fuels (coal, natural gas, and oil). Coal, as a primary energy source, accounted for 36.7% of the total electricity generation in the world [1]. However, the combustion of coal emitted 44% of the total CO_2 emission from fuel combustion. It leads to harmful effects on human life in general. The thermochemical process is the most popular in coal-based power generation. The thermochemical process includes the combustion, pyrolysis, and gasification processes. Presently, coal gasification is considered as the centre of clean coal technology.

Gasification is a thermochemical process, in which using heat and gasifying reactants convert carbon-based materials into a combustible gas mixture. This combustible gas can be used in heat and power generation, as well as in the chemical synthesis process as the main advantage of the gasification process. In the gasification process, the gasifying reactants can be listed as air, oxygen, carbon dioxide, steam, super-critical water, and their combination. In which, steam is a popular reactant in the case of hydrogen-rich gas production [2]–[4].

In the Institute of Energy and Quality, the University of Miskolc, the steam gasification process is investigated in both single- and multi-stage types. In both systems, the requirements for the steam generator are: (i) the steam has to be introduced at a high temperature (300 °C) to prevent the unexpected increase of pressure inside the gasifier; (ii) continuously provided steam flow rate during the experiment without interruptions; and (iii) at a steam flow rate that can be accurately controlled and adjusted during the experiment. In

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the initial design, the steam was provided by a Maxi Vapor steam generator, with 3.5 L of a built-in tank, 1300 W of power, and 2.8 bar of vapour pressure inside the tank *(Figure 1)* [5]. The drawbacks of this steam generator are the limit in the tank volume and the manual control of steam flow rate, that can only be adjusted at the initial setup of the experiment by measuring the weight loss of the system. Several types of steam generators can be found in the market [6]–[8], but they are purpose built for specific industries as the previously used Maxi Vapor steam generator or have very high cost compared to their performance.

Figure 1
The Maxi Vapor steam generator

This paper provides the development and setup of a steam generator that was created specifically for the steam gasification process at our research facility.

1. Material and methods

The schematic diagram of the steam generator is shown in *Figure 2*. The apparatus of the steam generator can be categorised into two different parts, the heating part, and the water flow rate control part. The heating part includes a PID controller, a solid-state relay, a heating coil, a thermocouple, and three quartz-tube electrical resistance heaters. The water flow rate control part includes a peristaltic pump head, a stepper motor, a stepper driver, and a microcontroller.

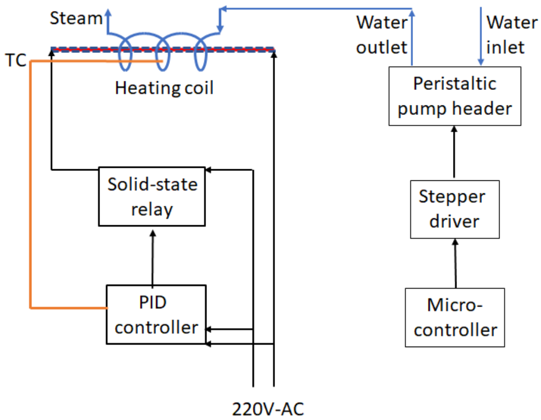

Figure 2
The schematic diagram of the steam generator

2. Results and discussion

2.1. The heating section

In the steam generator, the steam is generated at high temperatures and ambient pressure in a heating pipe made from heat resistant steel, that wound up in a coil (heating coil). The heating coil is made of heat-resistant steel with 8 mm of outer diameter (*Figure 3)*. The heat required for steam generation is supplied by three quartz-tube electrical resistance heaters. The total power of all three electrical heaters is 1800 W. There is a thermocouple inserted at the outlet of steam required for the PID controller.

Figure 3
The heating coil of the steam generator

During the steam generation process, the temperature in the core of the heating coil can reach 350 °C. Therefore, the heating coil is covered by a ceramic insulation layer with 25 mm of thickness to prevent heat loss. The whole heating coil is placed in an aluminium case with a dimension of 600 × 250 × 200 mm *(Figure 4*). The solid-state relay [9] and PID controller [10] are placed in a plastic box *(Figure 5)*, which is designed in Autodesk Fusion 360 [11] and printed by a UP300 3D printer [12] with PETG material [13].

Figure 4
The case of the heating coil

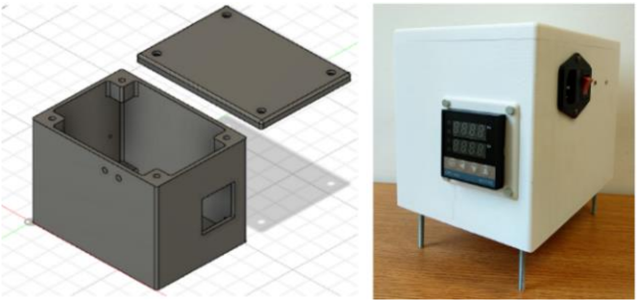

Figure 5
The controller box of the steam generator

2.2. The water flow rate control

The circuit diagram of the water flow rate control system is presented in *Figure 6*. The main controller used in this prototype is an Arduino nano due to its low-cost and compact properties. This microcontroller works on 5V level logic and supports the Serial peripheral interface and I^2C communication. An LCD 1602 display is used to indicate the water flow rate during the experiment [14]. The communication between LCD 1602 display and microcontroller is achieved through the I2C protocol. Several stepper drivers can be used to control the stepper motor, such as the A4988 driver, DRV8825 driver, or TB6600 driver. In which, the A4988 driver is used in this scope due to its simple operation and low-cost properties [15]. It works between 3.3 and 5V logic supply and the power supply for steeper motor from 9 to 36 V. Each pulse from the microcontroller to the STEP pin of the A4988 driver will correspond to one micro step of the stepper motor. The STEP pin is connected to the D3 pin of the microcontroller. The DIR-direction pin of the A4988 driver is connected D2 pins of the microcontroller, with only low and high values to select the clockwise and counterclockwise direction of the stepper motor. The EN-enable is linked to the D7 pin of the microcontroller. The high level at the D7 pin will return the enable status of the driver. The VMOT pin (16) and GND pin (15) of the driver are used for the power supply of the steeper motor. The 1A, 1B, 2A and 2B pins of the driver are connected to the stepper motor. There is a rotary encoder installedto vary the water flow rate in this steam generator. The A, B, and SW pins of the rotary encoder are coupled with the D4, D5, and D6 of the microcontroller.

The control signals are created through the rotation of an encoder knob. These signals are processed in the microcontroller, and then the speed of the stepper motor is adjusted through the communication between the microcontroller and driver A4988. The water flow rate and delay time as control parameters are presented on an LCD. The prototype of the water flow rate control circuit is illustrated in *Figure 7-(a)*.

The stepper motor used in this research is a NEMA17 bipolar type with 0.42 Nm of torque, 12 V and 0.5 A of power supply [16]. The peristaltic pump head is used in this research with 5 mm of outer diameter and 3 mm of inner diameter of the flexible tube (or pump tube) [17]. The stepper motor and pump head are presented in *Figure 7-(b)* and *-(c)*, respectively.

The following stage was to design a printed circuit board for the whole system. The circuit diagram and PCB model were designed in Easyeda-an online PCB design tool [18]. The advantage of this design tool it's ease of use with an abundant library of parts and components. The designed circuit board and printed circuit board with electronic components are depicted in *Figure 8*.

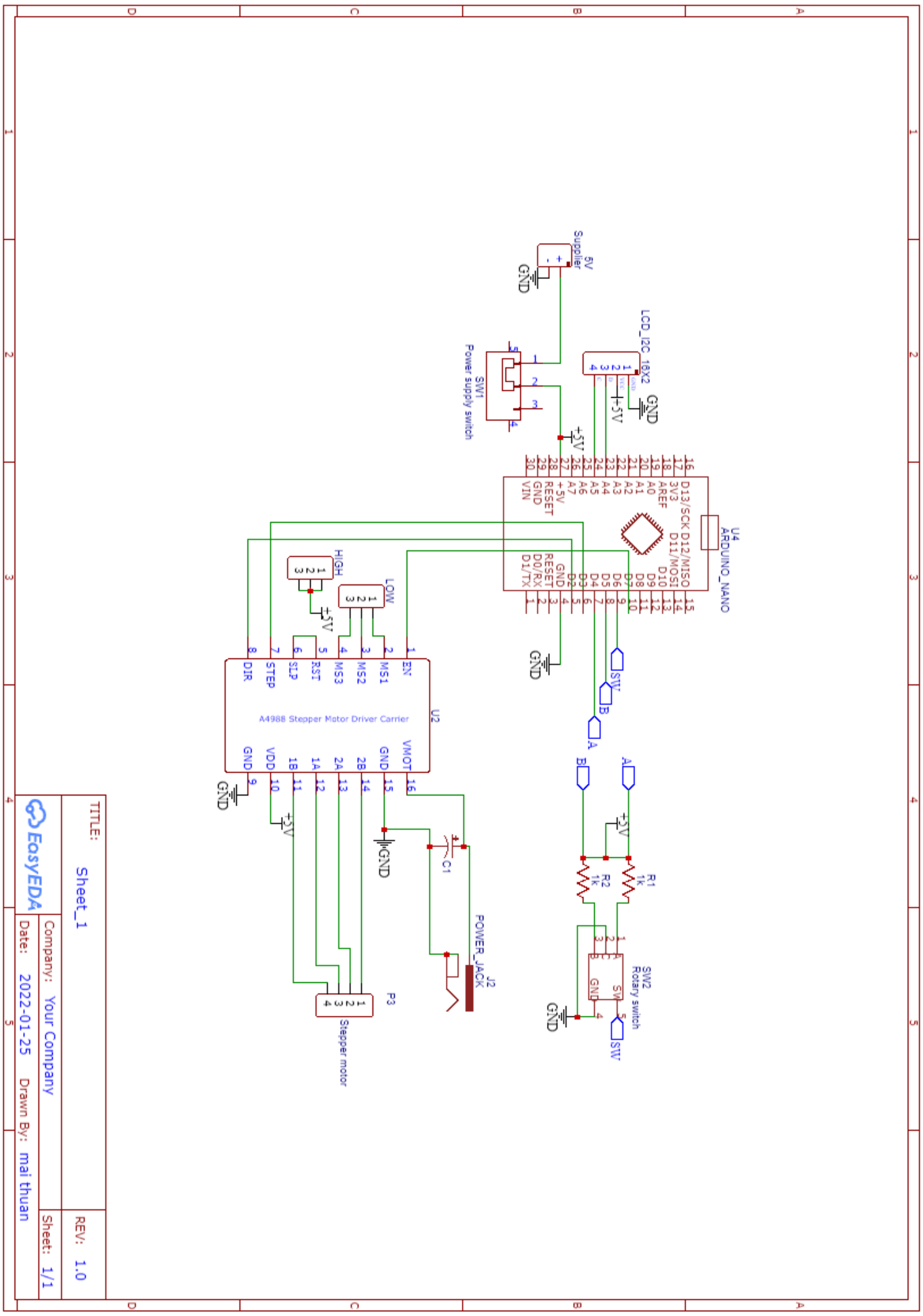

Figure 6

The wiring diagram of the control circuit of the water pump

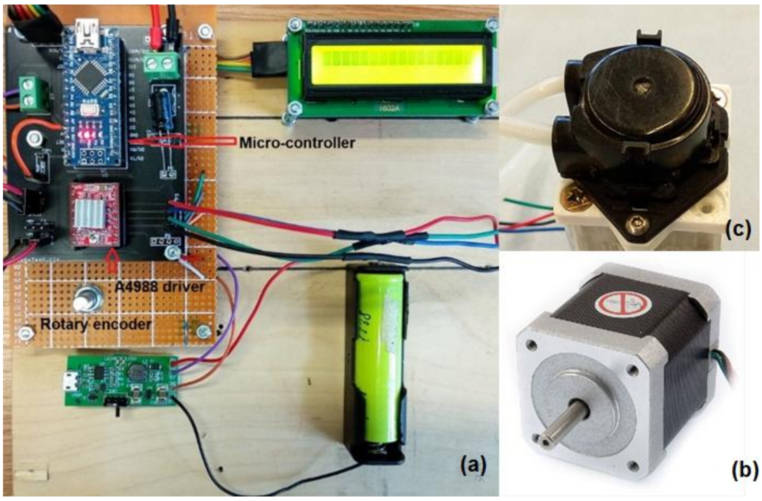

Figure 7
(a) Prototype of the control system of water flow rate; (b) Stepper motor; (c) peristaltic pump head

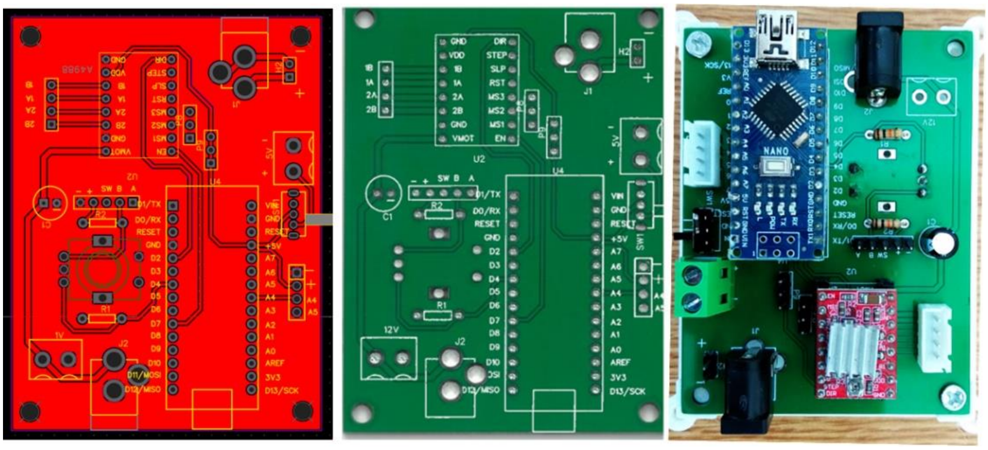

Figure 8
The PCB of the water flow rate control system

2.3. Software for the water flow rate control circuit

The Arduino software environment (Arduino IDE) [19] is used to program the microcontroller. The written program is called a sketch. This sketch will be uploaded to the microcontroller board through a USB cable.

The sketch usually is constructed in two sections, the setup section and the loop section. The setup section includes the libraries required, the definition of the variables and constants, as well as the initial assignment of the pin function.

In this research, the library required includes Wire.h and LiquidCrystal_I2C.h library. The Wire.h library allows the I2C communication between the microcontroller and the I2C device. The LiquidCrystal_I2C.h library allows controlling LCD 1602 display from the microcontroller in this scope. There are three more small groups followed to use for the assignment of the driver pins and rotary encoder knob pins *Figure 9*. The “delaytime” is the delay time between two pulses to the stepper driver. It will be calculated by the microcontroller based on the water flow rate.

```
#include <Wire.h>
#include <LiquidCrystal_I2C.h>
LiquidCrystal_I2C lcd(0x27, 16, 2);
// The driver pins:
const int stepPin = 3; const int dirPin = 2; const int enPin = 7;
// The variables of switch
int value; int oldValue = 0; int state = 0;
const int ledPin = 13;
//The rotary encoder knob pins:
int encoder0PinA = 4; int encoder0PinB = 5;
const int swPin = 6; int encoder0Pos = 10;
int encoder0PinALast = LOW; int n = LOW;
int maxKnob = 46; float delaytime; float delaytimenew;
```

Figure 9
The sketch of libraries and assignment of pins

```
void setup() {
  lcd.begin(); lcd.backlight(); lcd.clear();
  lcd.setCursor(0, 0); lcd.print("W:"); lcd.setCursor(6, 0);
  lcd.print("("); lcd.setCursor(11, 0); lcd.print(")");
  lcd.setCursor(0, 1); lcd.print("D:"); lcd.setCursor(8, 1);
  lcd.print("#");

  pinMode (swPin, INPUT_PULLUP);
  pinMode (encoder0PinA, INPUT);
  pinMode (encoder0PinB, INPUT);

  pinMode(stepPin, OUTPUT);
  pinMode(dirPin, OUTPUT);
  pinMode(enPin, OUTPUT);
  // Set Dir
  digitalWrite(dirPin, LOW);
}
```

Figure 10
The sketch of the setup section

The next part of the setup section is “void setup” where the LCD, the A4988 driver and the rotary encoder knob are initiated *(Figure 10)*. The setup section is followed by the void loop section. The containing codes in the void loop section will be cycled through the microcontroller after the upload *(Figure 11)*. The microcontroller will perform the code line by line in the void loop section. In the void loop section, from the first line to the line noted as “the botton was released” is used to indicate the initial status of driver, as well as to perform the task when the button of the rotary encoder knob is pushed.

```
void loop() {
  value = digitalRead(swPin);
  if (value && !oldValue)
  {
    if (state == 0)
    {
      digitalWrite(enPin, LOW); delaytimenew = delaytime;
      digitalWrite(ledPin, HIGH); lcd.setCursor(9, 1);
      lcd.print(delaytimenew); state = 1;
    }
    else
    {
      digitalWrite(enPin, HIGH); digitalWrite(ledPin, LOW);
      state = 0;
    }
    oldValue = 1;
  }
  else if (!value && oldValue)
  {
    oldValue = 0; // the button was released
  }
  motorStep(0); getKnob();
}
```

Figure 11
The sketch of the loop section

The “motorStep” function is used to create the working pulse for the A4988 driver within the “delaytime” *(Figure 12)*. While the “getKnob” is used to set the desired water flow rate and translate it into the “delaytime” based on the given equation *(Figure 13)*.

```
void motorStep( int MAX) {

  digitalWrite(stepPin, HIGH);

  delayMicroseconds(delaytimenew);

  digitalWrite(stepPin, LOW);

  delayMicroseconds(delaytimenew);

}
```

Figure 12
The sketch of the motorStep function

```
void getKnob() {

  n = digitalRead(encoder0PinA);

  if ((encoder0PinALast == LOW) && (n == HIGH)) {

    if (digitalRead(encoder0PinB) == HIGH) {encoder0Pos--;
    } else {
      encoder0Pos++;
    }
    if ( encoder0Pos > maxKnob ) {
      encoder0Pos = maxKnob;
    }
    else if ( encoder0Pos < 18 ) {
      encoder0Pos = 18;
    }
    float wfr6 = encoder0Pos * 0.5;
    float r = 25472 * pow(wfr6, -1.052);
    delaytime = r;
    float wfr20 = wfr6 / 3.3;
    lcd.setCursor(2, 0);
    lcd.print(wfr6, 1);
    lcd.setCursor(7, 0);
    lcd.print(wfr20, 1);
    lcd.setCursor(2, 1);
    lcd.print(r, 1);
  }
  encoder0PinALast = n;
}
```

Figure 13
The sketch of the getKnob function

2.4. The operation of steam generator

One of the most important keys in this section is to understand the characteristic of heater elements, in both PID parameters and adaptation time at various water flow rates. The maximum capacity of the steam generator was designed at 1800 W within the maximum water flow rate of 20 g/min, required by the multi-stage gasification system the is developed at our research facility. Furthermore, it is necessary to reduce the adaptation time when the water flow rate is changed. Therefore, the autotuning of the PID controller was set at 10% higher than the maximum designed water flow rate (22 g/min), and the temperature was set at 300 °C. The autotuning process was illustrated in *Figure 14*, it finished after 725 seconds. After the autotuning process, the p, i, and d parameters were 742, 120, and 30, respectively. However, the temperature in the steam generator only reached 300 °C in the autotuning process, after that it settled at around 245 °C. With the max water flow rate in the autotuning process is higher than the original designed value (20 g/min), therefore the heating elements did not have enough power to drive these steam generation processes at the setting value of temperature (300 °C).

The temperature profile of the steam generator within different water flow rates was presented in *Figure 15* at the above p, i, and d values. The results indicated that the average time to reach a stable temperature was 30 minutes for each water flow rate. When the water flow rate shifted to another value, the temperature decreased to 121 °C. After that, the temperature increased to the initially set value. When the water flow rate is suddenly changed to a lower value the temperature of the steam generator at the steam output could suddenly increase to a higher temperature than it was originally set up to. Therefore, the flow rate has to be changed in small steps of 2.5÷5 g/min. This initial temperature drops and increase of flow rate could be fine-tuned within the sketch of the microcontroller. However, this does not represent an issue during a gasification experiment as the changes in the experiment settings usually require considerably longer time. The measured surface temperature of the steam generator case did not increase above 50 °C during the test period.

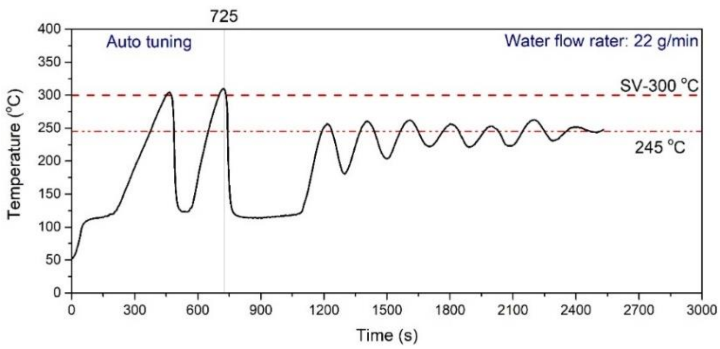

Figure 14
The auto-tuning process of the PID controller

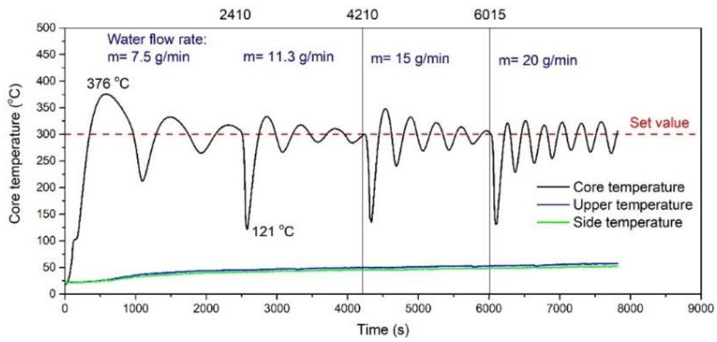

Figure 15
The temperature profile of the steam generator

CONCLUSION

The development and setting up of a steam generator have been presented, with the water flow rate controlled by a microcontroller. The total power of the steam generator is 1800 W, while the water mass flow rate can be varied between 1 toand 20 g/min. The produced steam can be set to a maximum of 300 °C for a continuous steam generation during the experiment. The main advantages of this steam generator the ease of operation, flexibility in case of changes required with mass flow rate, temperatures, connection to the PLC controller and low cost of build.

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