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Ignition Behavior of Benzoic Resin Solid Fuel Pellets over a Surface Induction Heating Plate Using a Liquefied Petroleum Gas Flame Ignitor

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ABSTRACT: In this paper, we introduce a novel and unprecedented solid fuel known as benzoic resin, which is equivalent to coal. Here, we focus on the ignition behavior of benzoic resin, and for this purpose, we have employed an induction heating plate equipped with a liquefied petroleum gas flame ignitor. Additionally, an analytical model was also developed to estimate the ignition rate of this solid fuel. Experiments were carried out for various induction heating surface temperatures, such as 70, 100, 130, 160, 210, 240, and 270 °C. The Fourier transform infrared spectral studies of benzoic resin exhibited two sharp peaks at a lower wavenumber. The calorific value of benzoic resin is found to be 26 004.92 kJ/kg, which is higher than lignite and bituminous coal, except anthracite. The ignition and volatile initial release temperatures were found to be 70 and 90 °C, respectively, where these values are better than the other coal types. Also, the electrical conductivity of benzoic resin was measured to be 1620 μs/cm, which is quite higher than the low- and medium-rank coals. The main experimental results revealed a linear variation of the heat release rate for varying surface induction steel plate temperatures. A visible ignition was detected at the surface temperature of 70 °C and the highest heat release rate of 260 J/s, which was achieved at 270 °C surface temperature. Furthermore, a soaring heat release rate was accomplished for an increasing combustion time, and also, good emission characteristics were quantified. Additionally, the ignition and heat release rate results were compared to other standard ASTM methods using an electric Bunsen burner and Meker−Fisher burner, which showed close correlation.

1. INTRODUCTION

A well-known potential solid fuel, coal, has transformed human civilization since the beginning of the Industrial Revolution. Coal is a basic component for generating electricity and production of steel and cement. The exploration and mining of coal have been carried out throughout the many parts of the globe, but its current demand is still unpredictable (in the state of the pendulum). The BP Energy Outlook 2017 forecasts that the energy demand will increase by 30% and coal will be one of the governing energy sources. Also, they predict that coal consumption at the global level is expected to peak and its demand is plummeting sharply.[6] Even the International Energy Agency (IEA) stated that, until 2021, the demand for coal will climb barely. This plunging coal demand is due to increasing CO_2 emission and hazards in the coal mines, such as coal outburst, explosion, etc.

The earlier literature shows the importance of the coal ignition study by different methods. Kim et al. analyzed the ignition behavior of various coal ranks and their pulverized particles with a flat flame burner under a high heating rate. Five different coals, such as lignite, anthracite, sub-bituminous, high-volatile bituminous, and medium-volatile bituminous, were used for experimentation, and a high-speed camera was deployed to capture the various ignition images of pulverized coal particles (<45, 75−90, and 150−200 μm). It was found that anthracite with a particle size in the range of 150−200 μm underwent homogeneous ignition after preliminary fragmentation. During ignition, most of the coal particles were fragmented, while the low-rank coal and lignite underwent homogeneous ignition with direct fragmentation. For the particle size of <45 μm, the medium-volatile bituminous coal underwent heterogeneous ignition but a homogeneous ignition occurred for high-volatile bituminous coal.[10]

Zhou et al. quantitatively measured the ignition temperatures of pulverized coal under oxygen and carbon dioxide conditions. Their results indicated that the ignition temperature of pulverized coal in 21% oxygen and 79% carbon dioxide is greater than in air. Additionally, the concentration of oxygen in an O_2 and CO_2 environment is increased to correlate with the coal ignition temperature in air.[15] Zhang et al. investigated the thermal acceleration, ignition, and combustion characteristic temperatures of coal char. The authors proposed a new

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model for the measurement of the ignition temperature of three different pulverized coal char. This was simultaneously measured using differential scanning calorimetry (DSC) and thermogravimetry. Their results showed that the coal char ignition occurs in the range between the inflection point temperature and minimum ignition temperature. It was found that the thermal gradient of lignite coal char is 1.6 times higher than anthracite and bituminous in the ignition zone and 3.4 times higher in the zone of combustion.[14] Even Avila et al. adopted a thermogravimetric analyzer and fluidized-bed combuster (FBC) for the examination of the coal ignition temperature. Also, their results showed a similar ignition temperature under these two conditions. Actually, the temperature of coal ignition was acquired by the gas concentration variations in the FBC. According to the authors, the ignition temperatures were entirely associated with coal combustion activation energy.[1]

Chao et al. investigated the ignition temperature of coal in an O_2-enriched fluidized-bed reactor (FBR), because this helps in the design of boilers and also for selecting the feeding temperature during the transition from oxy- to air-firing conditions. Five types of coals were subjected to the ignition and combustion process under four different atmospheric conditions, such as O_2 with 27, 40, and 53% and air. These were estimated in the lab-based FBR with a system of preheat under bed. Changes in the bed temperature and different component concentrations in a flue gas were measured using a thermocouple and an exhaust gas analyzer, for the determination of the ignition temperature of coal. It was observed that, for an increasing concentration of oxygen, the coal ignition temperature simultaneously reduces. Additionally, the two-stage ignition process was noted in a specific oxygen concentration and initial bed temperature; this was observed at lower bed temperatures.[4] Thus, the earlier reports indicated the significance of the coal ignition for various applications, especially in the design of thermal systems and understanding the heat and mass transfer within that system.

The present investigation attempts to fill the existing market gap by elucidating a new solid fuel called benzoic resin, which would be an alternative to coal. Benzoic resin is a balsamic resin that is synthesized using different species of tree bark from the genus *Styrax*.[5,16] Actually, it is an incense, which is commonly used by Indians, Chinese, Japanese, and Russians for ritual and other similar purposes[8] (Figure 1 shows a typical image of a benzoic resin solid pellet). In this paper, we claim that the benzoic resin is a potential solid fuel, which mainly has a gross calorific value (GCV) of 26 004.92 kJ/kg, and for many decades, its potential has not been fully realized. Certainly, this product can be considered as an alternative or even a replacement for solid and pulverized coal.

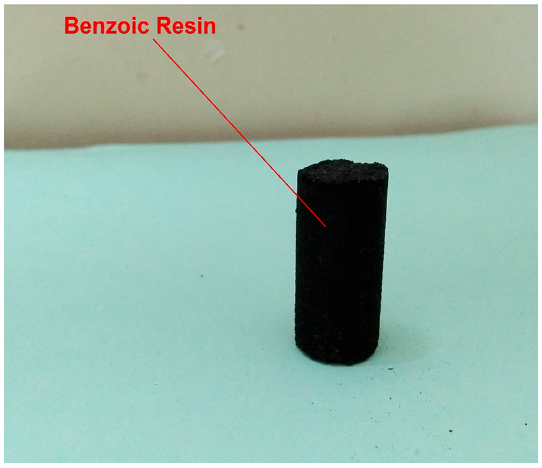

Figure 1. Typical picture of a benzoic resin solid pellet.

An enormous amount of this resource is available in nature, and it is difficult to provide the exact quantity. Actually, this is a processed fuel that is taken from barks of several balsam trees, which are native to Indonesia, India, and several Southeast Asian countries. Mostly, these kinds of trees are found in the tropics and widely spread over 1000 ha. The origin and chemical composition of this benzoic resin biomass can be explored in the literature.[16]

The comparison of benzoic resin to a coal is possible through their chemical compositions, which are similar. A tree bark can be considered as a biomass, whereas a coal is a fossil. However, the common thing between those two are fuel. Obviously, the formation of these two fuels are different, but their fuel chemical properties are almost similar. We have to agree with the common fact that the consumption rate of coal is enormous, and its cost per unit energy is still cheaper than biomass. It can be seen from Figure 2 that the processing charge of this fuel is cheaper. It is a processed fuel, and it can be achieved in a warehouse, unlike a coal, which should be mined and processed. The cost of one pellet (produced from a factory) is Rs 3 ($0.046). Therefore, the processing cost for this fuel pellet is very inexpensive. The processing charge of the raw material that is the tree bark is somewhat costly. However, the final product is still cheap. Business men in India are exporting these benzoic resin pellets to many countries across the globe as an incense. Overall, at this current time, we feel that the economic analysis of this fuel is not that much more significant.

We are conducting an investigation on the successful quantification of ignition characteristics of coal under induction heating (IH) regimes. Generally, the knowledge about the ignition behavior of various coals is essential in the design of a furnace and other thermal engineering systems. Because this helps in the determination of temperature gradients in that system, this paper also tries to the fill the literature gap of the ignition behavior of the benzoic resin solid fuel as a function of the surface temperature.

2. MATERIALS AND METHODS

This section presents the materials and methods that are adopted in this investigation. Figure 2 presents the benzoic resin production process, and it can be seen from this figure that the raw material (bark) is obtained from several different species of tree bark of *Styrax* latex. First, the bark and its latex fluid from the tree bark will be acquired, dried, then sent to the torrefaction stage, and pulverized according to different mesh. During this process, essence and perfumes will be added to obtain the aroma. Subsequently, it will be sent to die work for producing benzoic resin in a definite geometry, usually in cylindrical shapes. Its standard dimensions are 2.8 cm in length with a diameter of 1.2 cm. Any desired shape and dimension can be produced with the help of die. Generally, benzoic resin is processed and produced with these specifications only, and after that, it will be sent to sales and marketing. The final processed product is used in the present investigation for testing and analysis.

Figure 3 shows the field emission scanning election microscopy (FESEM) images of the benzoic resin pellet. Nearly, six images were presented in the magnification ranges of 1, 2, 10, and 20 μm. Panels a, b, d, e, and f of Figure 3 revealed a honeycomb structure, which also indicates a microlevel porous space, while Figure 3c shows the

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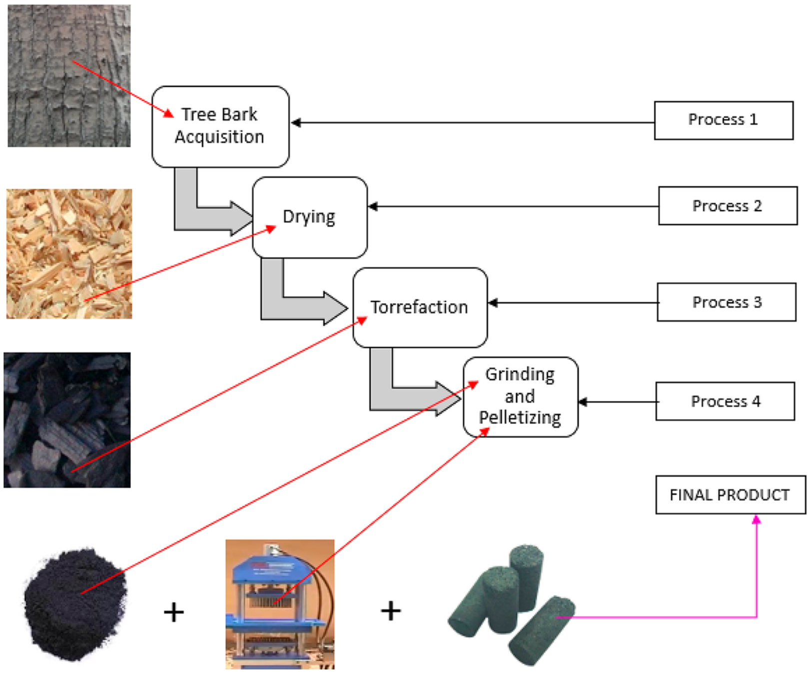
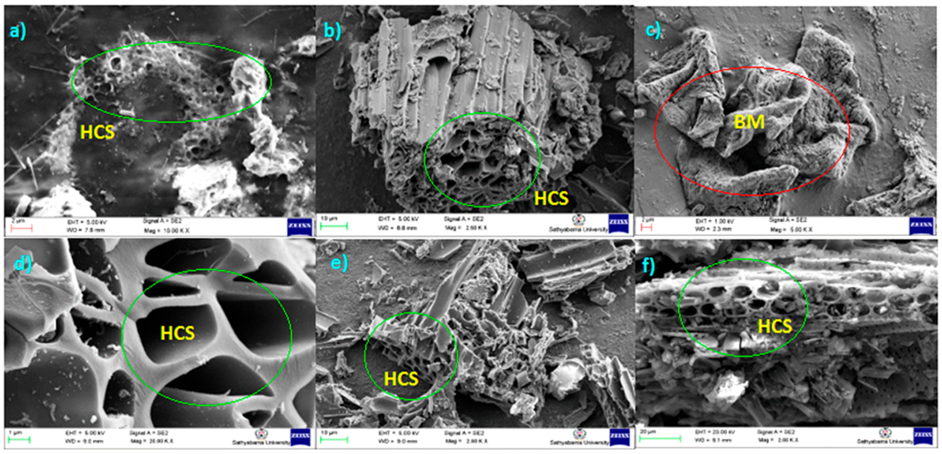


Figure 2. Benzoic resin production process.



HCS = Honeycomb Structure; BM = Binding Material; a) = 2μm, b) = 10μm, c) = 2μm, d) = 1μm, e) = 10μm, f) = 20μm

Figure 3. FESEM images of the benzoic resin.

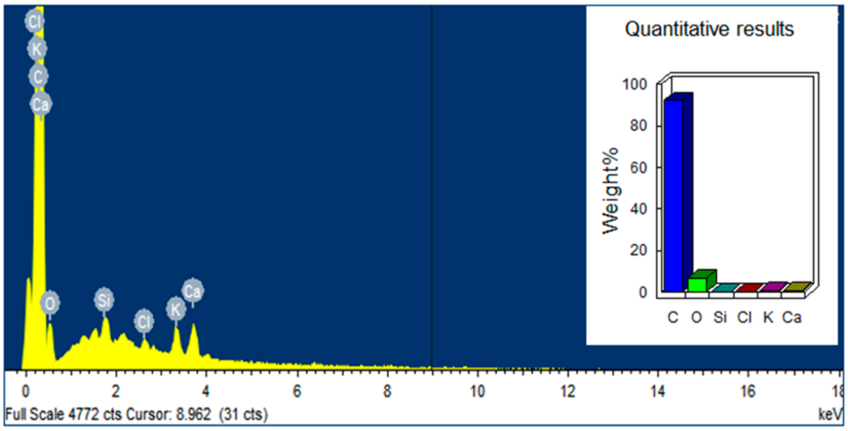


Figure 4. EDAX spectrum of the benzoic resin.

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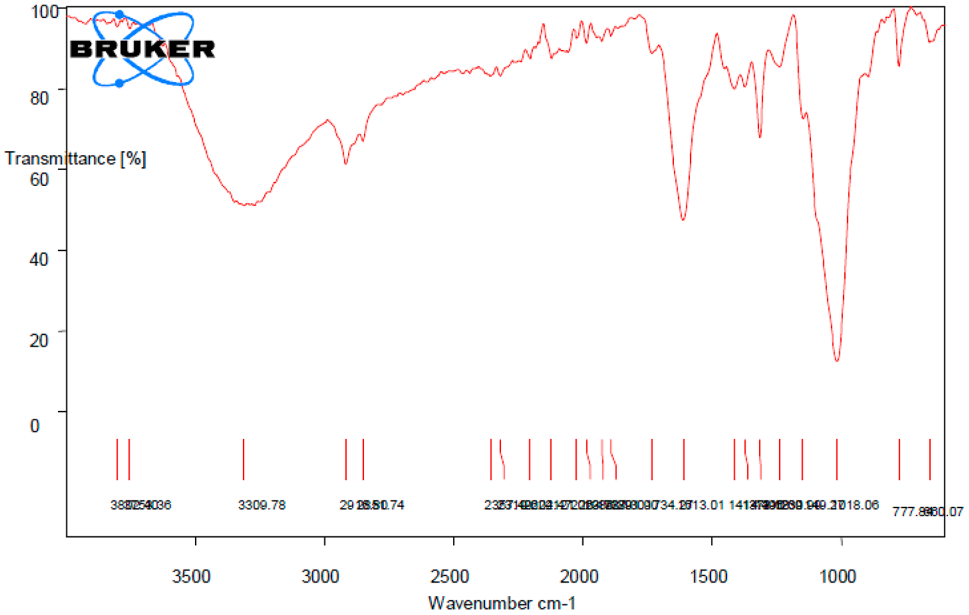

Figure 5. FTIR spectrum of the benzoic resin.

Table 1. Major Fuel Properties of the Benzoic Resin and Other Coals

property	unit	lignite	bituminous coal	anthracite	benzoic resin
gross calorific value	kJ/kg	16410.57	23326.00	33445.71	26004.92
ignition temperature	°C	273	440	730	70
volatile initial release temperature	°C	150	242	395	90
electrical conductivity	μS/cm	876	1293	2944	1620
bulk density	kg/m^3	645	728	890	334
ash content	wt %	4.3	8.1	14.5	19.2
carbon content	wt %	32.3	53.8	82.4	72.6
moisture content	wt %	38	7.9	13.8	2.6
sulfur content	wt %	0.41	0.74	0.66	0

binding material or binder. This indicates that the basic resin could have bonded with other elements during the production process. Figure 4 indicates the energy-dispersive X-ray spectroscopy (EDAX) image. It can be clearly seen that the benzoic resin has the chemical composition of 90% carbon, 8% oxygen, 1% calcium, 0.60% potassium, 0.30% chlorine, and 0.10% silicon. Even a typical composition of coal is about 70−90 wt % carbon, with other elements consisting of oxygen, hydrogen, sulfur, and nitrogen, which fall in the range of 10−30 wt %. It should be noted that the benzoic resin has no sulfur content, as evident from the EDAX image.

Figure 5 presents the Fourier transform infrared (FTIR) spectrum of the benzoic resin solid pellet. The three major peaks indicate the possibility of carbon−carbon and carbon−hydrogen bonds. The low intensity peak at 2920 cm^{-1} indicates the presence of the C−H bond, while the C−O stretching frequency is observed at 1020 cm^{-1}. The band at 3310 cm^{-1} indicates the stretching frequency of the O−H group.

Table 1 shows the major fuel properties of the benzoic resin, and it has been compared to other coal grades. It can be viewed from the table that most of the benzoic solid fuel properties are better than low- and medium-rank coals. The gross calorific value (GCV) is considered as a lifeblood for any fuel. It is surprising to see that the GCV for benzoic resin is 26 004.92 kJ/kg, which is higher than those of lignite and bituminous coal but less than that of anthracite coal. The benzoic resin electrical conductivity is less than that of anthracite but higher than those of lignite and bituminous coal. The ignition temperature of benzoic resin is 70 °C, which is lower than those of other coals; by this, it means that the ignition occurs even at the lowest temperature or, in other words, the ignition can be achieved with less energy. Also, its volatile initial release temperature is 90 °C; besides, its bulk density is low (less weight). Interestingly, it was found that this solid chunk of benzoic resin has no sulfur content. However, coal contains a few percentages of sulfur, which, upon combustion, will produce SO_2 emissions in addition to carbon dioxide. Emitted sulfur dioxide undergoes oxidation in the atmosphere to form H_2SO_4, which subsequently produces acid rain. Therefore, the fuel properties of benzoic resin suggest that this would be a potential alternative solid fuel in the near future.

The coal reserves throughout the world are rapidly being exhausted, and almost 850 billion tons of coal are left for mining and extraction. Furthermore, it will last for about 150 years if there is a continuation in the current consumption rate.[11].[2] Hence, this paper brings out a novel alternative solid fuel to meet the future energy demand. Importantly, it was found that the ash content of the benzoic resin is 19.2 wt %, which is larger than anthracite, lignite, and bituminous coals. Generally, after the combustion of coal, huge quantities of ash are left underneath the furnace. This ash will be used in the furnaces of brick, steel, and cement industries to maintain the temperature level in the furnace, because this determines the degree of reaction rates.[13] Likewise, the ashes produced from the benzoic resin can also be used in these furnaces to sustain the temperature and control the reaction rate.

Some reasearchers may argue that this kind of compressed solid fuel incense cannot be compared to coal, and for them, a high amount of ash may seem to be a big problem. We illustrate that, basically, a compressed incense can be considered as a fuel because its origin is wood (and bark), which is fundamentally a fuel. We have compared and associated this processed solid pellet fuel to coal based on their chemical properties. The chemical properties of coal and benzoic resin are similar, and additionally, a high amount of ash is not a

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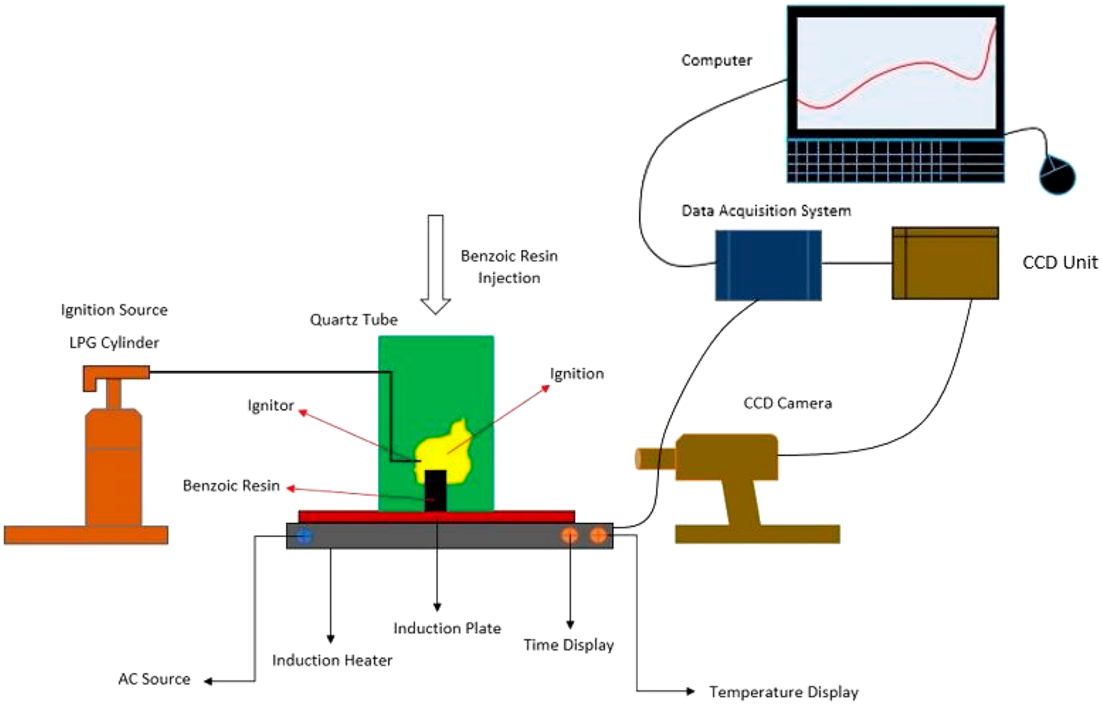

Figure 6. Schematic diagram of the experimental setup.

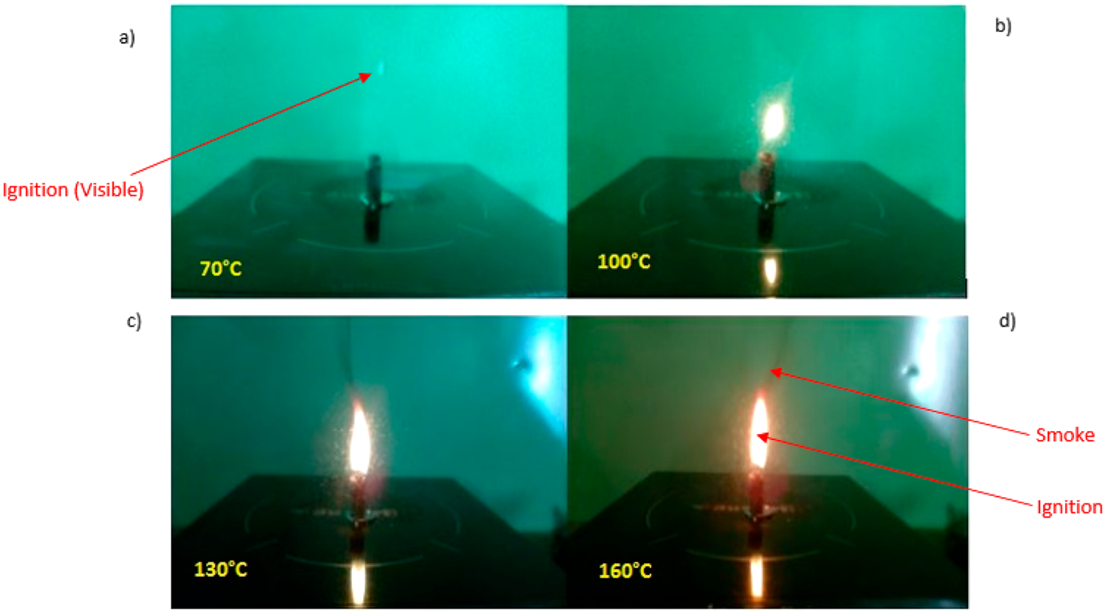

Figure 7. Ignition of benzoic resin pellets at various surface temperatures: (a) 70 °C, (b) 100 °C, (c) 130 °C, and (d) 160 °C.

serious problem because it does not affect the thermal efficiency of a system. For instance, for the furnaces in the metallurgical and power plants, huge quantities of coal will undergo combustion, and consequently, a higher amount of ash will be left as a residue after and during the burning process. In this case, the thermal efficiency of the furnace and its mechanical output will not be affected in anyway. Even the ash has been recycled in the thermal system for sustaining the combustion rate. Overall, we strongly believe that our work falls under the scope of the energy and fuel domain, and this research should be considered as a matter of significance and worthy of investigation.

The schematic layout of the experimental setup is given in Figure 6. It consists of an induction heater, which is covered with a steel plate that was given a black coating. Over this, benzoic resin solid fuel is placed for ignition testing. The induction heater is connected to an alternating current (AC) source, and it is equipped with a time and temperature display. IH is gradually becoming popular for ignition and combustion analysis of both solid and liquid fuels. IH has been used in the industry for heat treatment applications for the past 3 decades. This is mainly due to good reproducibility and rapid heating.[9] Dronbenko et al. suggested that high-temperature IH of cylindrical solids, which are electroconductive, develops thermal stresses. Because this will enhance the reaction rate of electroconductive solids, residual stress in the solids can be achieved.[7]

The metal plate is heated through an induction mechanism that is from electrical energy to thermal energy. We can control the temperature settings (input), and heat energy is widely distributed in all areas of the plate. Then, the benzoic resin pellet is placed in the

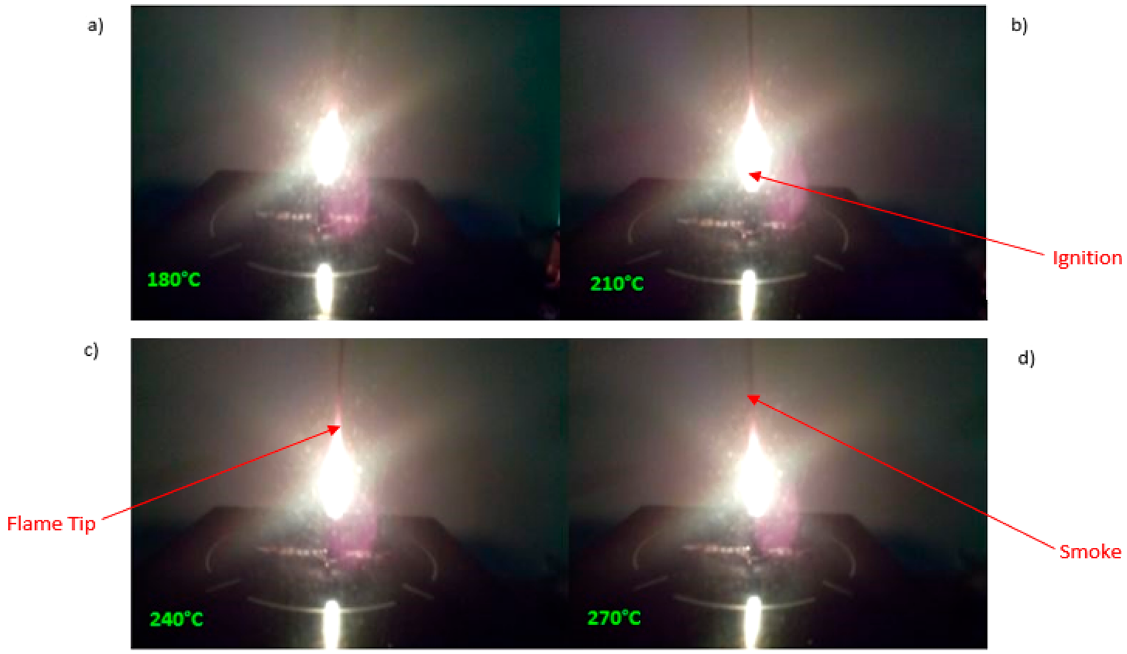

Figure 8. Ignition of benzoic resin pellets at various surface temperatures: (a) 180 °C, (b) 210 °C, (c) 240 °C, and (d) 270 °C.

center of the plate, and through conduction, the heat passes from the plate to the pellet. The liquefied petroleum gas (LPG) flame ignitor was placed aside to trigger the ignition on benzoic solid, and on the other side, a charge-coupled device (CCD) camera is placed to capture the ignition images. The CCD camera is connected to a CCD unit and then to a data acquisition system (DAS). However, the induction heater is directly connected to DAS and then overall connected to a computer system, which is installed with the AVL 6000 Delta version software package to analyze the ignition rate and heat release rate (HRR) of a fuel over an IH plate. However, our proposed experimental method is validated with standard experimental procedures using a Meker−Fisher burner (MFB) and an electric Bunsen burner (EBB), and the results are in good agreement with each other. The ultimate goal of this investigation is to study the ignition behavior of benzoin resin as a function of IH. The next section critically analyzes the ignition characteristics and HRR of the benzoic resin under surface IH conditions.

3. RESULTS AND DISCUSSION

3.1. Ignition Characteristics. This section critically discusses the ignition characteristics of the benzoic resin as a function of the surface temperature. Initially, during the start of the experiment, there is no observation of fire or ignition but there is a high amount of smoke/fume release. The aim of this paper is to acquire the images of ignition (fire) of benzoic resin. Therefore, camphor nanoparticles were embedded on the top circular face of the benzoic solid, and a new solid is placed for each test. Examining the characteristics of camphor particles is beyond the scope of this paper. It should be noted that the camphor particles on the top face of the benzoic resin pellet are only acting as a catalyst. This was performed to achieve the flame and capture its image. Moreover, it does not alter or affect the heating rate of the benzoic resin or volatile fumes. Figures 7 and 8 show the various ignition behaviors of the benzoic resin solid over the IH plate with surface temperatures of 70, 100, 130, 160, 180, 210, 240, and 270 °C. For the first domain that is between 70 and 160 °C, the experiment was conducted with a quartz tube, and later, it was removed for the second range (180−270 °C).

It can be seen from Figure 7a that the first visible observation of benzoic solid ignition was captured at the IH surface temperature of 70 °C. This could be attributed to the physical ignition delay that is upon LPG ignition; the benzoic solid vaporizes and will mix with air. This ignition delay is reduced at higher surface temperatures. The ignition temperature of benzoic resin is near 70 °C; hence, it indicates that the ignition can be detected with a minimum surface temperature. At 100 °C surface temperature, a partial ignition was achieved, and full ignition was captured at the surface temperatures of 130 and 160 °C. It can be observed in this set of experiments that there is a release of smoke during and after ignition in a laminar and transition movement. Also, it implies that there is a large exchange of heat energy between the bottom circular face of benzoic solid and the induction surface plate. Because the heat is transferred from the induction plate to benzoic solid through the conduction mechanism, then upon ignition, radiative heat is liberated to the surroundings. It shows that benzoic solid has a high amount of enthalpy, and in the near future, this will be tested for the production of any mechanical work.

In the second set of experiments, a complete image of benzoic ignitions was observed (Figure 8). It can be observed from Figure 8a that, at the surface temperature of 180 °C, a slight transition ignition behavior was exhibited by benzoic solid fuel. The same transition ignition behavior was also noted at 210 and 270 °C surface temperatures. The implication for this behavior may be due to a variable surface temperature distribution across the plate. However, at 240 °C surface temperature, a laminar ignition was displayed by benzoic resin, and this may occur during sporadic steady-state conditions of the induction surface plate. Even at these higher surface temperature experiments, there is a subsequent release of smoke in a very thin laminar flow. For instance, at 210 °C, the benzoic ignition is carried out with a very thin laminar smoke, and this smoke starts at the end of the flame tip. Therefore, the ignition characteristics of the benzoic resin were critically analyzed in this section, and the following section explores the analytical model for this problem.

3.2. Analytical Model. First, the impulse of the ignition is determined by the following equation:

$$\alpha_i = \frac{\Delta\psi}{\pi(r^2 + 6)} \tag{1}$$

where α_i indicates the initial time of ignition impact and $\Delta\psi$ is the change in the thermal potential that is the calorific content of the solid benzoic resin pellet with respect to its cross section. Then, the modified governing fluid momentum is mentioned for the ignition flame in the z direction, which is given by ref 12

$$\rho u_z r \frac{\partial u_z}{\partial z} + \rho u_r r \frac{\partial u_z}{\partial_r} = -r\frac{\partial p}{\partial z} + \frac{\partial}{\partial r}\left(\mu r \frac{\partial u_z}{\partial r}\right) \tag{2}$$

The physical variables ρ and μ indicate the density of the pellet and the ignition flame fume viscosity, respectively, and obviously, r denote the radius. After that, the internal energy of the benzoic resin solid fuel is given by

$$\Delta U = W + PV \tag{3}$$

where ΔU is the change in internal energy in seconds that is a product of work done and pressure and volume. Next, the following equation is applied for the HRR measurements:

$$Q_r = \frac{T_f - T_i}{R} - C_p \frac{dT_\tau}{dt} \tag{4}$$

where Q_r is the HRR, which is the difference in the temperature and specific pressure during the ignition reaction of the benzoic pellet. Subsequently, the sublimation reaction of the benzoic resin over the IH steel plate is given by

$$\eta_s = \frac{m_i - m_{\Delta t}}{m_i - m_\beta} \tag{5}$$

where $m_{\Delta t}$ is the sample mass that varies with time, m_i is the initial mass of the sample, and m_β is the remaining sample mass after ignition. Then, the modified radiative transfer equation (RTE) can be written as

$$\Delta\Omega = \Delta U + T_\tau(\eta_s) - t_\tau(\eta_s) \tag{6}$$

where $\Delta\Omega$ is the change of heat transfer to the radiation mechanism. This is the product of change in internal energy and the difference in overall temperature and time, which is the function of surface energy (η_s) in dyn/cm. In this case, we assume both one-dimensional (1D) and two-dimensional (2D) flow of heat transfer, and then the required equations can be presented as follows:

for 1D heat flow

$$\frac{\partial u}{\partial t} = \alpha^2 \frac{\partial^2 u}{\partial x^2} \tag{7}$$

for 2D heat flow

$$\frac{\partial u}{\partial t} = \alpha^2\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \tag{8}$$

where α is the heat flow rate (J/s) with respect to time. The thermal conductivity of the benzoic resin is presented below. For uniform thermal conductivity (W m^{-1} K^{-1}) over the induction plate

$$K_c = \left(\frac{T_{max} - T_{min}}{\Delta U}\right) 2\pi r(h + r) \tag{9}$$

Then, for variable thermal conductivity over the induction plate

$$K_v = \Delta U \times 2\pi r(h + r)\left(\frac{T_{max} - T_{min}}{L}\right) \tag{10}$$

Temperature variation with respect to heat flux is given by

$$K_q = \frac{1}{(T_{max} - T_{min})^2} \int_{t_2}^{t_1} [\Delta U f(t)\, dt] \tag{11}$$

The heat emission from the benzoic resin solid chunk is given by

$$Q_e = H(1 - \alpha^2)\pi r^2 + H(1 - \alpha^2)^2 \pi r^2 [1 - 2\pi r(h + r)] + ... \tag{12}$$

The heat liberation from the benzoic resin and induction plate (surface/interface) is written as

$$Q_{BR} = \frac{t\frac{dQ}{dt}}{(T_{max} - T_{min})\frac{\Delta H}{\beta_{t_2}}} - Q_s \tag{13}$$

$$Q_{IP} = \frac{t\frac{dQ}{dt}}{(T_{max} - T_{min})\frac{\Delta H}{\beta_{t_1}}} - Q_{if} \tag{14}$$

The cumulative heat liberation (Q_{chr}) is given by

$$Q_{chr} = Q_{BR} + Q_{IP}$$

$$Q_{chr} = \frac{t\frac{dQ}{dt}}{(T_{max} - T_{min})\frac{\Delta H}{\beta_{t_2}}} - Q_s + \left[\frac{t\frac{dQ}{dt}}{(T_{max} - T_{min})\frac{\Delta H}{\beta_{t_1}}} - Q_{if}\right] \tag{15}$$

Therefore, the above equation can be rewritten as

$$Q_{chr} = \frac{t\frac{dQ}{dt}(-Q_s - Q_{if})}{(T_{max} - T_{min})\Delta H\left(\frac{1}{\beta_{t_2}} - \frac{1}{\beta_{t_1}}\right)} \tag{16}$$

Hence, eq 16 can be used for calculating the HRR over a surface plate operating through IH. Thus, analytical modeling was successfully applied to this problem. In this section, we have presented an analytical model, whose accuracy is relative and not absolute. We have provided this to predict the cumulative HRR of the benzoic resin pellets over the IH plate and have compared our analytical model values to experimental values and revealed good agreement, which can be explored in the following sections.

3.3. HRR Analysis. This section discusses and analyzes the HRR characteristics of benzoic resin. These HRR curves were acquired by the AVL combustion analyzer software during ignition tests. The solid benzoic resin HRR curves for increasing IH surface temperatures and combustion time are given in Figures 9 and 10. As viewed from Figure 7, the rate of

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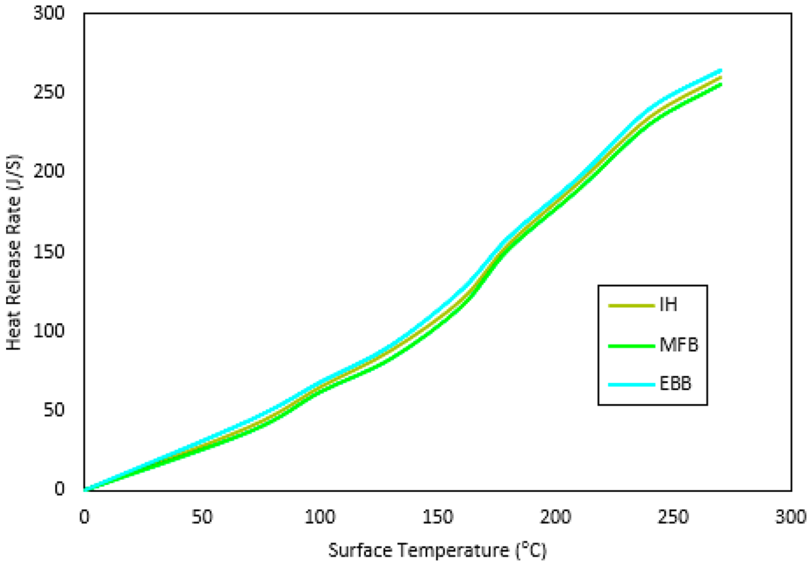

Figure 9. HRR for varying surface temperature.

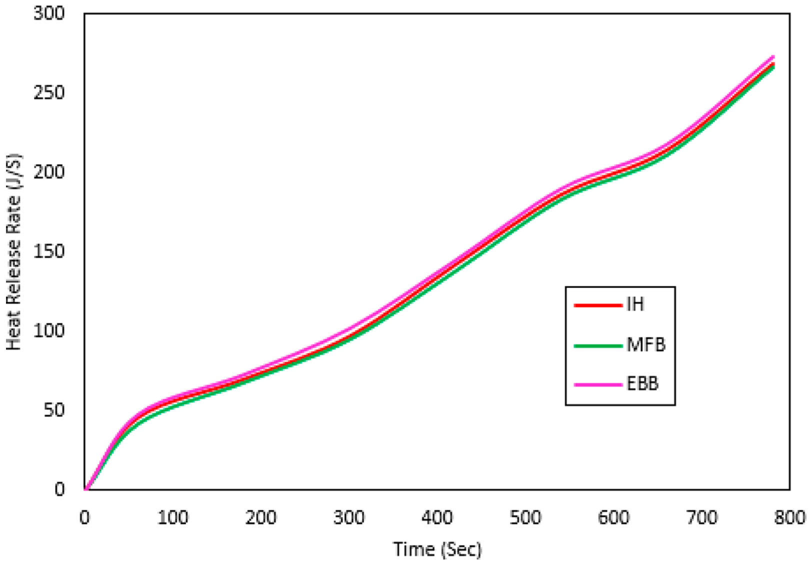

Figure 10. HRR for varying time.

heat release from benzoic resin over the induction thermal plate is gradually increasing. Initially, at 70 °C surface temperature, 40 J/s was recorded, and a 65 J/s heat release was noted at the plate surface temperature of 100 °C. Between these two surface temperatures, the heat release is 25 J/s. Then, at 130 °C, the HRR is found to be 88 J/s, and a steep increase in the HRR is observed at 180 °C surface temperature, which gives the HRR value of 155 J/s. Generally, the HRR is associated with the GCV of fuel, and the benzoic resin has a good calorific content that is higher than lignite and bituminous coals. Finally, the HRR curve reaches 260 J/s at the surface temperature of 270 °C, which is regarded as the maximum value. Similar values were observed for the methods employing an EBB and a MFB. Both showed similar curves, and a higher HRR was achieved in the EBB system.

The maximum HRR corresponding to each combustion time is shown in Figure 10. Even in this case, 46 J/s was initially observed for the combustion time of 60 s for IH, whereas 42 and 48 J/s were observed for MFB and EBB, respectively. Then, for IH of the benzoic pellet, 70 J/s was noted for 180 s and soaring to a maximum of 268 J/s. This value is obtained for the combustion time of 780 s and leaving a large quantity of ash as a residue. It is implicated that the premixed solid fuel benzoic resin ignites rapidly and releases enormous amounts of heat with supplement smoke. The higher HRR was observed for the combustion time of 13 min, which indicates that the energy content per unit mass is higher compared to lignite and bituminous coals. It should be noted that HRR is actually a heating value of benzoic resin and not volatile fumes. Typically, the heating value of coal falls between 30 499 and 33 412 kJ/kg. On the whole, in this case, also, the benzoic resin HRR with respect to time is higher for EBB, which implies that the EBB produces higher HRR that IH and MFB methods. However, it does not show any significant difference, and their values are closer. The benzoic resin pellet HRR through the IH method exhibited higher and exceptional HRR. Its performance is higher than that of MFB and quite lower than that of EBB, and importantly, it should be noted that the input energy for accelerating the HRR is almost the same for all of the methods.

The higher HRR determines the energy content per unit mass. This is because of the fuel calorific value and, for example, considering an internal combustion engine. The refined fuels, such as diesel, gasoline, and LPG, will produce a higher HRR and cylinder pressure and, consequently, enhance the thermal and mechanical outputs of that system, whereas biofuels deliver only a moderate amount of heat release and pressure as a result of less calorific content. In this case, it is obvious that a higher heating rate of refined fuels shows a higher energy content per unit mass of the fuel. This mechanism is also applicable for the benzoic resin case, having a higher GCV and carbon content and, consequently, enhancing the HRR, which, in turn, shows the energy content per unit mass of the fuel pellet. Therefore, it illustrates that benzoic solid fuel at a higher burning rate results in the enhancement of the diffusion burning phase because of its oxygen content.

Because the GCV of benzoic resin is higher than that of bituminous coal, we shall associate the energy content per unit mass of this fuel pellet with the medium-rank coal. Slyusarskiy et al. reported that the HRR of a bituminous coal depends upon the calorific content, the activation energy, and mainly the kinetic properties of the coal. They have taken Siberian bituminous coal for the analysis and found that a lower net calorific value (NCV) reduces the activation energy and, therefore, runs the risk of losing the rate of heat release during combustion.[18] Even Jones et al. experimented with the Scottish bituminous coal and came out with a conclusion that the kinetic rate and activation energy determine the HRR, and this is the sign of energy content per unit mass of a fuel.[17] Figure 11 shows the model validation of this experimental work. The correlation was plotted between the surface temperature and the HRR. The analytical model (eq 6) and the experimental methodology values were taken for calculation. It can be seen from Figure 11 that there is a close agreement between the models. Thus, the reliability of the model is good and has been successfully demonstrated. Hence, the analytical model for the heat release is confirmed and validated with the experimental results.

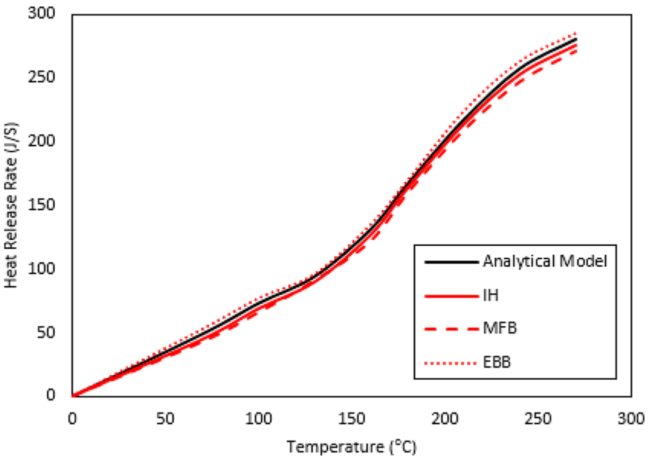

Figure 11. Validation of experimental models.

The emission characteristics of benzoic solid fuel are presented in Table 2. A total of 100 g of pulverized benzoic resin was burnt in a mini furnace, and its exhaust line is connected to the exhaust gas analyzer, alhough the analysis of benzoic resin emission characteristics is not the main theme of this paper but just presented for curiosity. The combustion process is set to burn for about 120 s, and after that, the exhaust port is opened and the gases were recorded in the exhaust gas analyzer. The results revealed a series of emissions, such as 0.23% carbon dioxide (CO_2), 20.69% oxygen (O_2), and 1 ppm of nitrogen (in the form of NO). Nitrogen emissions may be due to a high inlet temperature in the furnace. Unburnt hydrocarbon (HC) and carbon monoxide (CO) emissions account for 23 ppm and 0.026%, respectively. These emission values, which are obtained from experimentation, are not completely perfect or accurate. Honestly, we should agree that uncertainties have arisen during experimentation. Especially, as a result of experimental design, in our future investigation, more emphasis will be given to study the benzoic solid fuel characteristics with different thermal systems and under various environments as well. Thus, this paper has successfully illustrated the significance of benzoic resin solid fuel ignition characteristics, and this resin can be considered as an alternative solid fuel to coal.

Table 2. Benzoic Resin Emissions

time (s)	CO (%)	HC (ppm)	CO_2 (%)	O_2 (%)	NO (ppm)
120	0.026	23	0.23	20.69	1

4. CONCLUSION

To the best of our knowledge, this is the first paper to elucidate and claim benzoic resin as a potential solid fuel, which is an alternative to coal. On the basis of the analytical modeling and experimentation, the following conclusions can be drawn: (1) First, benzoic resin has an outstanding chemical property, which is better than lignite and bituminous coals, except anthracite. After combustion, the ash weight percentage of benzoic resin is exceptionally high and can be directly used in the steel and cement industries. This is to maintain their furnace temperatures for the successful reaction. (2) A visible ignition was observed at the surface temperature of 70 °C, and the ignition rate gradually increases for varying higher surface induction plate temperatures. The ignition is accompanied by smoke, which releases linearly in the upward direction. Also, an analytical model was successfully developed to evaluate and predict the changing ignition behavior of benzoic resin. (3) Benzoic resin showed a heterogeneous ignition, which is characterized by the exchange of heat between the induction plate and the bottom circular face of the solid fuel.[3,12] (4) A linear increase of HRR was observed for varying surface temperatures and combustion time. The maximum HRR of 260 J/s was achieved at 270 °C surface temperature, and 301 J/s was acquired at the combustion time of 780 s. The HRR curves from the IH method were compared to standard ASTM methods using MFB and EBB. All three showed similar values, and there was a good correlation among them. (5) Emission characteristics of the benzoic resin were also recorded. For 120 s of combustion, some various gases were released, such as CO, HC, CO_2, O_2, and NO. However, particularly in this emission experimentation, there are many uncertainties that might have arisen during testing and the experimental design/method. This process will be rectified and investigated rigorously in our future investigations.

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Notes

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NOMENCLATURE

IH = induction heating
MFB = Meker–Fisher burner
EBB = electric Bunsen burner
W = work done (J/N)
P = pressure (bar)
V = volume (m^3)
R = gas constant ($J\ K^{-1}\ mol^{-1}$)
L = length (cm)
H = enthalpy (J/kg)
t = time (s)
u = internal energy (J/kg)
h = height (cm)
r = radius (cm)
i = initial
z = z coordinate
m = mass (kg)
ρ = density (kg/m^3)
μ = gas viscosity (cP)
ψ = thermal potential (J/K)
β = energy conversion efficiency (%)
Δ = change in the physical quantity
α = heat flow (J/s)
α_i = ignition impact with respect to the ith time (initial time)
t_1 = initial time (s)
t_2 = maximum time (s)
t_τ = overall time (s)
T_f = final temperature (s)
T_s = initial temperature (°C)
T_τ = overall temperature (°C)
T_{max} = maximum temperature (°C)
T_{min} = minimum temperature (°C)
Q_r = heat release (J/s)
Q_e = heat emission (J/s)
Q_s = heat content over solid fuel (J/A)
Q_{if} = heat content between the plate and bottom benzoic resin interface (J/A)
Q_{BR} = heat liberation from benzoic resin solid (J/s)
Q_{IP} = heat liberation from the plate and benzoic solid interface (J/s)
Q_{chr} = cumulative heat release (J/s)
K_c = uniform thermal conductivity of the induction plate ($W\ m^{-1}\ K^{-1}$)
K_v = varying thermal conductivity of the induction plate ($W\ m^{-1}\ K^{-1}$)
K_q = surface heat flux ($W\ m^{-2}$)
C_p = specific pressure (bar)
η_s = surface energy (dyn/cm)
Δt = change in reaction time (s)
ΔU = change in internal energy (s)
ΔH = change in enthalpy (J/kg)
$\Delta\Omega$ = change of heat transfer as a result of the radiation mechanism (J/s)

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