Design and Implementation of a Coalbed Methane Extraction Device Using Microwave Radiation

Ali Jebelli
University of Alberta https://orcid.org/0000-0001-8364-3244
Arezoo Mahabadi
Tehran University
Rafiq Ahmad (rafiq.ahmad@ualberta.ca)
University of Alberta https://orcid.org/0000-0001-9353-3380

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Design and implementation of a coalbed methane extraction device using microwave radiation

Ali Jebelli[1], Arezoo Mahabadi[2], Rafiq Ahmad[1*]

[1]Laboratory of Intelligent Manufacturing, Design and Automation (LIMDA), Department of Mechanical Engineering, University of Alberta, 9211 116 Street NW, Edmonton, Canada
[2]School of Engineering Science, Tehran University, Tehran, Iran
*Corresponding Author: rafiq.ahmad@ualberta.ca,

Abstract

The continuous growth of the population and the global economy increases the need for sustainable energy. To this end, the recovery factor of hydrocarbon resources in the world should be maximized. One of the main sources of natural gas is coalbed methane, a gas accumulated in pores inside coal. On the other hand, methane gas explosion is a potential hazard in coal mines, which causes many casualties every year in coal mines worldwide. Mine ventilation alone cannot create a safe environment for coal mining due to the high volume of gas released in some coal seams. Therefore, Methane gas extraction can turn one of the major hazards in coal mining into a clean energy source and have dual benefits. Unfortunately, the permeability of most coal seams is very low, and this low permeability limits the development and production of commercial coalbed methane. Therefore, coalbed methane reservoir stimulation is an attractive option because the relative permeability of natural fractures in the coal seam and the surrounding rock greatly affects the amount of extractable gas. Microwave radiation is one of the new methods to increase the permeability of coal. In this research, we design, simulate and implement a small, lightweight, portable microwave gun that uses a conical horn with an aperture of 28 cm with a working frequency of 2.45 GHz to evaporate the moisture in the circle with a diameter of 40 cm from a coal wall and increases the permeability of the wall due to microwave radiation. Because in previous studies, the tests were performed only on large and small capacity devices without any control over the amount of microwave radiation and by replacing the gas inside the chamber with argon or nitrogen gases, which does not represent the real conditions in the mines. Therefore, by building a small device, we have overcome the limit of coal size and amount. By considering the coal ignition temperature, we have provided the challenges related to removing oxygen from the air and the possibility of working in real conditions in mines with larger volumes of coal, which is very similar to the mining environment. Also, the proposed small and portable device in this paper allows us to use it in different environments.

Keywords: Microwave gun, Coal permeability enhancement, Conical horn, Coalbed methane, Microwave heating, Methane.

1. Introduction

Coalbed methane is a natural gas that is adsorbed in coal. In other words, gas is adsorbed on the surface of the coal and stored in micropores or placed in natural coal fractures [1]. Large coal resources around the world make it possible to extract significant amounts of methane gas. In recent years, in an effort to reduce environmental issues, countries have begun to search for and exploit coal for clean gas energy, which is also associated with the use of coal [2]. Despite the benefits mentioned for methane gas, this gas has different percentages in different ore compositions. The highest percentage of methane gas is found in coal, which causes the risks of explosion, flare, and environmental pollution. Sometimes mine ventilation systems are not enough to drain this gas [3-4]. For this reason, existing methane gas is extracted in the mines before and during coal mining, which is highly dependent on the permeability of the coal.

Permeability is one of the properties of rock that shows the ability of fluid (gas or liquid) to flow through rocks, which is related to the pressure of the study environment. Permeability is part of the proportionality constant in Darcy's law that relates to the flow rate of the physical properties of a fluid, such as viscosity. The measurement unit of permeability is square meters (m^2) in the SI system and darsi (d) or often milli-darsi (md) in applied problems (1d $=10^{-12}$ m^2). [5]. Darcy was the first to describe the process of flowing water through sand filters for drinking water.

Artificial physical (fracture) or chemical (acidification) methods are used to create more permeability and flow in rocks (such as dense, compact, or non-porous rocks).

Due to the possible negative effects of the hydraulic fracturing method, this method of coal mining is prohibited in some countries. For this reason, cracking of the coal surface using microwave heating of coal has been suggested [6]. Microwave radiation is widely used in coal processing fields such as drying, coking, pyrolysis, flotation, increasing grindability, and magnetic removal [7].

In previous studies, the air inside the chamber was filled with argon gas or nitrogen in tested in laboratory conditions (that were different from the actual environment) to prevent ignition [8,9]. In this paper, various parameters affecting the electric field and heat of the system were tested and simulated in real conditions. Finally, a device tailored to the needs of the system was installed to extract methane gas from the coal inside the mine, considering the coal ignition temperature and the tested parameters. In previous studies [3,5,8,10,11], small controlled cavities for heating coal have been used to control the coal ignition temperature, but these experiments are not feasible in real conditions. On the other hand, the possibility of methane gas explosion and human and financial damage and environmental pollution causes the need to extract methane gas before or during coal extraction is more important than its extraction after coal extraction, which is not possible in previous studies.

2. Theory

Microwave propagation and heat transfer in the chamber must be modeled to calculate the amount of heat absorption and heat transfer in a microwave chamber.

2.1. Symbols

The list of symbols used in this paper is summarized in Table 1.

Table 1- Table of symbols.

Name	electric field intensity(V/m)	magnetic field intensity(A/m)	electric current density(A/m2)	wavelength	Permeability (electromagnetism)
Symbol	E	H	J	λ	μ
Name	conductivity	angular frequency	surface normal vector	permittivity	free space wave number
Symbol	σ	ω	n	ε	k_0
Name	Relative permeability	Relative permittivity	absolute temperature (K)	heat source(W/m3)	velocity vector of translational motion(m/s)
Symbol	μ_r	ε_r	T	Q	u
Name	density (kg/m3)	specific heat capacity at constant stress (J/(kg·K))	heat flux(W/m^2)	material's conductivity	Time(s)
symbol	ρ	C_p	q	k	t
Name	the mass averaged velocity vector (m/s)	a reaction rate expression for the species (mol/(m^3·s))	the mass flux diffusive flux vector (mol/(m^2·s)	the concentration of the species (mol/m3)	diffusivity (diffusion coefficient) (m2/s)
Symbol	u	R	J_m	c	D_c
Name	specific moisture capacity	Rayleigh number	length	Cutoff frequency	Speed of light
Symbol	C_m	Ra_L	L	fc	C_0
Name	moisture conductivity	Dynamic viscosity of the fluid kg/m.s	mass transfer coefficient	Aperture efficiency	Antenna gain
Symbol	k_m	v	k_c	e_A	G
Name	the slant length of the cone from the	Diameter of aperture of antenna	Flare angle of antenna	Scattering parameter	

	apex				
Symbol	L_a	d	θ	S11	

In this paper, ∇ is the gradient, ∇. is divergence and ∇ × denotes the curl operator.

2.2. Maxwell Equation

The Maxwell equation governing electromagnetic waves inside a microwave oven is as follows [12]:

$$\nabla \times \mu_r^{-1}(\nabla \times E) - k_0^2\left(\varepsilon_r - \frac{j\sigma}{\omega\varepsilon_0}\right)E = 0 \tag{1}$$

In which the permeability coefficient of the vacuum or air magnetic field is $4\pi \times 10^{-7} H/m$ and the permeability coefficient of the vacuum or air electric field is $8.854 \times 10^{-12} Farad/m$ [13-15].

2.3. Heat transfer

Heat transfer in materials is done by conduction, convection, and radiation. Heat in liquids is often transferred by convection, in which case the movement of the liquid itself transfers heat from one place to another. Another method is to transfer heat through conduction, in which there is no movement of matter, but rather the transfer of energy within that substance by contact with another substance. The third way to transmit energy by radiation involves the absorption or irradiation of electromagnetic waves.

The increase in body temperature in a non-uniform isotropic medium is obtained by solving the following equation [16]:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \bar{u}.\nabla T + \nabla.(q) = Q_{vap} + Q_{MW} \tag{2}$$

In which q includes the conduction heat flux and the radiant heat flux.

$$q = q_{rad} + q_{cond} \tag{3}$$

Q_{vap} is the latent heat of evaporation of coal moisture and Q_{MW} heat caused by microwave radiation. Fourier's law of heat transfer states that in a continuous environment, the conductive heat flux q_{cond} is proportional to the temperature gradient:

$$q_{cond} = -k.\nabla T \tag{4}$$

According to Newton's Law of Cooling, the convective heat flux depends on the temperature difference between the surface of the body and the environment (the fluid around the body).

$$q_{conv} = hA_s(T_{surface} - T_{fluid}) \tag{5}$$

The heat exchange rate of pure radiation is also as follows:

$$q_{rad} = \alpha\beta A_s\left(T_{surface} - T_s\right) \tag{6}$$

where $0 < \alpha < 1,\ \beta = 5.67 * 10^{-8}\ {}^{W}/_{m^2K^4}$

2.4. Initial conditions

1. The initial temperature of all objects is equal to the ambient temperature of 293.15 [K].
2. The initial electric field is zero.
3. The operating frequency value of the antenna input port is equal to 2.45 GHz.
4. The operating frequency is considered as much as 1.2 times the cut-off frequency of the circular waveguide.
5. TE_{11} emission mode is considered for cylindrical waveguide [17].

2.5. Boundary conditions

The impedance boundary condition is considered for antenna and waveguide walls, the governing relationship of which is as follows [13]:

$$\sqrt{\frac{\mu_0\mu_r}{\epsilon_0\epsilon_r - j\frac{\sigma}{\omega}}}\, n \times H + E - (n.E)n = 0 \tag{7}$$

In coal walls, the assumption of natural convection is considered:

$$-n.q = \Delta T * \begin{cases} \frac{k}{L}\left(0.68 + \frac{0.67 Ra_L^{1/4}}{\left(1+\left(\frac{0.492k}{vC_p}\right)^{9/16}\right)^{4/9}}\right) & if Ra_L \leq 10^9 \\ \frac{k}{L}\left(0.825 + \frac{0.387 Ra_L^{\frac{1}{6}}}{\left(1+\left(\frac{0.492k}{vC_p}\right)^{9/16}\right)^{8/27}}\right)^2 & if Ra_L > 10^9 \end{cases} \tag{8}$$

2.6. Assumptions

The following hypotheses are considered to simplify the designed problem:

1. The microwave only heats the coal and has no effect on the air.
2. The material of the antenna and waveguide is assumed to be aluminum.
3. Coal is isotropic and homogeneous.
4. The electrical, magnetic, and thermal properties of coal are constant.
5. The loss of electric waves in coal is the only reason for the increase in sample temperature.
6. Ignition temperature of coal was considered to be 360°C (equivalent to 633.15K) [18].

3. System design

3.1. waveguide

The cutoff frequency is the minimum wave frequency that can propagate in a waveguide. The cutoff frequency depends on the mode of propagation and the dimensions of the waveguide, and its value is a function of the roots of the Bessel functions and its derivative. Table 2 lists some of the roots of these functions. The frequency of the TE_{mn} propagation mode depends on the roots of the Bessel (X'_{mn}) derivative, and the frequency of the TM_{mn} propagation mode depends on the roots of the Bessel (X_{mn}) functions.

Table 2- Root of Bessel functions and root of Bessel functions' derivative.

Function number	Root number	Roots of the Bessel function J_m	Roots of the Bessel function derivatives J'_m
m	n	X_{mn}	X'_{mn}
0	1	2.405	3.832
0	2	5.520	7.016
0	3	8.654	10.173
1	1	3.832	1.841
1	2	7.016	5.331
2	1	5.136	3.054
2	2	8.417	6.706
3	1	6.380	4.201

The cut-off frequency of the TE_{mn} mode in a circular waveguide is calculated as follows:

$$f_{c,m,n} = \frac{C_0}{2\pi} \frac{X'_{m,n}}{radius}$$
(9)

And TM_{mn} cut-off frequency is calculated as follows:

$$f_{c,m,n} = \frac{C_0}{2\pi} \frac{X_{m,n}}{radius}$$
(10)

Therefore, according to Table 2, the dominant mode in circular waveguide is equal to TM_{11}.

3.2. Antenna

According to Figure 1 the following relation is used in an optimum conical horn antenna to have the maximum gain of the antenna and the minimum reflection [19]:

$$d = \sqrt{3\lambda L_a}$$
(11)

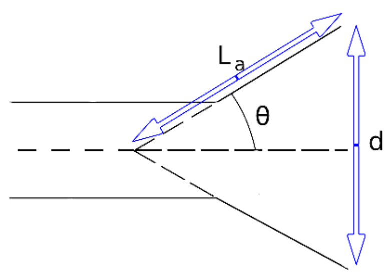


Figure 1. Conical antenna with aperture diameter d and flare angle = θ.

The gain of the conical horn antenna is also calculated as follows [19]:

$$G = \left(\frac{\pi d}{\lambda}\right)^2 * e_A \qquad (12)$$

4. Methodology

In this simulation, first, the electric field propagated in the environment is calculated according to Maxwell equations using Comsol software and the method of scattering microwave waves in the environment, and the amount of waves lost inside the coal is obtained. Then the temperature distribution of the sample and its heat transfer to the environment is obtained using the Fourier equation in the time domain, and the changes in coal moisture are simulated by calculating the mass transfer in coal. The characteristics of the horn antenna and its waveguide are calculated and specified in Table 3 and Figure 2.

4.1. Calculation of the sizes

Dominant mode is TE_{11} cylindrical waveguide, and since the desired operating frequency is 2.45 GHz and 1.2 times the cut off frequency, the radius of the waveguide is calculated as follows:

$$2.45 * 10^9 = 1.2 * f_{c,1,1} = \frac{C_0}{2\pi} \frac{1.841}{radius} \qquad (13)$$

$$\rightarrow radius = 0.043\ m$$

If the flare angle of the antenna is 35 degrees, the dimensions of the antenna are as follows:

$$d = 2L_a * \sin(35) = \sqrt{3\lambda L_a} \rightarrow \ L_a = \ 27.91\ cm\ , d = 32.01cm \tag{14}$$

Table 3- Antenna sizes and their waveguide.

Waveguide radius	0.043[m]
Waveguide length	0.10[m]
Flare angle	35[deg]
Diameter of antenna aperture	28[cm]
Horn thickness	0.003[m]
Radius of the circumferential circle	1.8 [m]
Cutoff frequency	2.043 [GHz]
Operation frequency	2.45 [GHz]
Radius of coal wall	0.7[m]
Thickness of coal wall	0.2[m]

The radiation pattern of the desired antenna is obtained by using simulation in COMSOL. Figure 2 shows the simulated radiation patterns of the proposed antenna. The maximum antenna gain is 16.81 dBi, and its s11 is -23.2dB, which is desirable [20-21]. The maximum aperture efficiency is 92%, according to the antenna size and operating frequency.

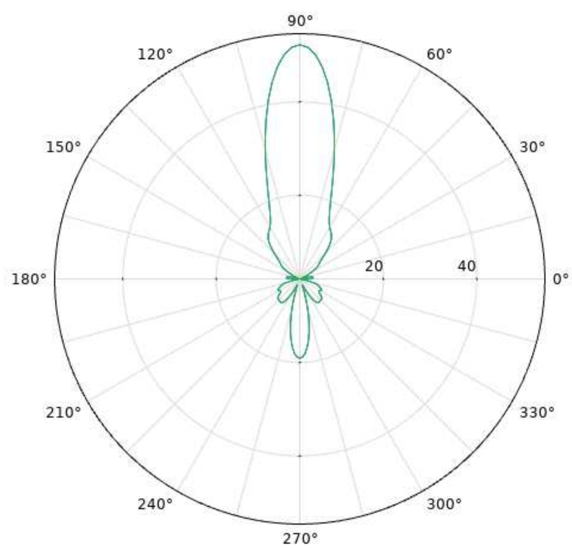


Figure 2. Radiation pattern of designed antenna (E-plane).

Therefore, the defined system, which can also be seen in Figure 3, includes a horn antenna with a flare angle of 35 degrees and an aperture with a diameter of 28 cm. A wall 20cm thick and 140cm wide with a distance of 93cm from the antenna opening is used to simulate coal. The defined materials can also be seen in Table 4.

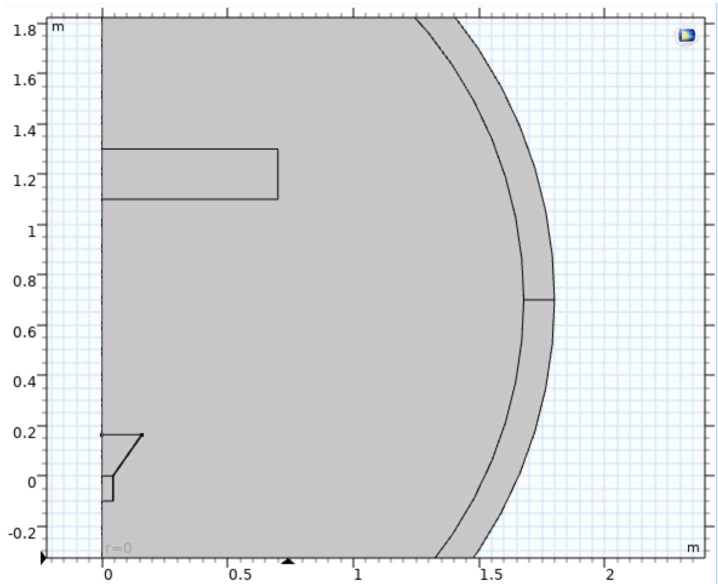


Figure 3. System defined according to Table 3.

Table 4- Specifications of materials at 293.15 K [22].

Name	Units			
		Coal	aluminum 6061-T6	Air
Relative permittivity(e’-e”j)	-	2.882-0.301j	1	1
Relative permeability(μ’-μ”j)	-	1	1	1
Electrical conductivity	S/m	0.02	$2.434*10^7$	0
Thermal conductivity	W/(m.k)	0.478	154.8	0.0256
Density	Kg/m^3	1300	2700	1.204
Heat capacity at constant pressure	J/(kg.K)	4186.8	896	1015.1

4.2. Mesh quality

According to the rule of thumb, the total number of geometry elements is 66000, with an average element quality of 95% suitable for meshing the system. The maximum system frequency of 3 GHz, equivalent to the maximum element size of 15 mm in a vacuum, leads to such quality in meshing. Figure 4 shows the optimal mesh quality and reliability of the final results. The selected material of the system is identified in Table 4.

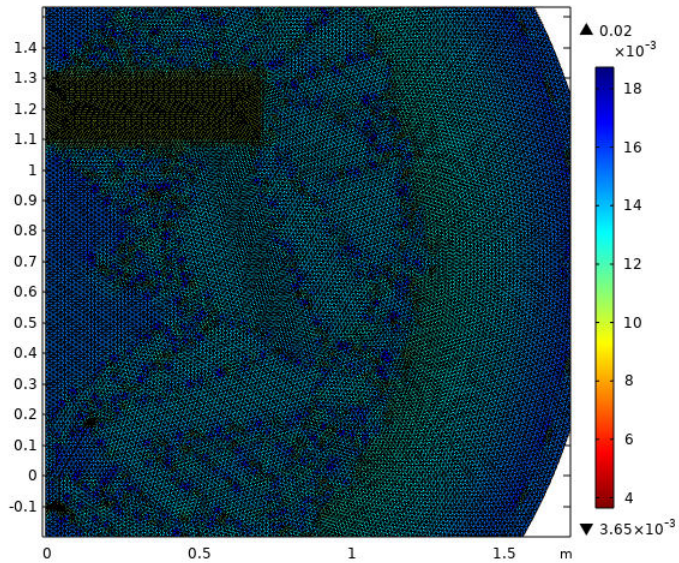


Figure 4. System meshing diagram based on elements size.

5. Simulation

Previous studies have tested in the laboratory condition, and the ignition temperature of coal has not been considered, or the system oxygen has been displaced with nitrogen or argon[6-11]. Experiments have also been performed in small containers under controlled laboratory conditions, which may be costly or impossible in mines to meet such conditions. In this paper, the real conditions of methane gas extraction in mines were met by designing a magnetron device as a source of wave generation and using a conical horn antenna to radiate the generated waves to the coal and consider its ignition temperature. The operating frequency and power are 2.45 GHz and 6 kW, respectively, and the moisture capacity of coal is 4.7%, which is exposed to microwave radiation for 5000 seconds. Figure 5 shows the electric field emitted in the environment. Although the coal wall is somewhat reflective of the electric field, the electric field is present only in the area between the coal wall and the antenna, and less than 0.005% of the electric field is scattered around.

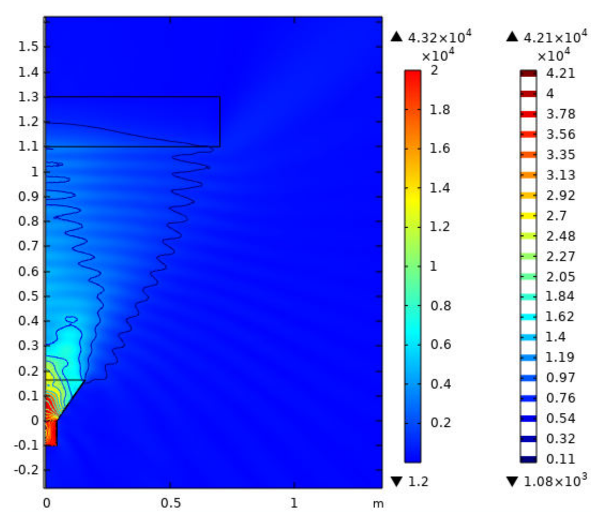


Figure 5. Scattering of the electric field radiated from the antenna to the coal wall. The maximum field occurs at $4.32*10^4$ V/m inside the waveguide.

Figure 6 shows the temperature diagram of coal. According to this figure, the designed system can evaporate the moisture in a circle with a diameter of 40 cm and a depth of 5 cm from the surface of the coal in a certain period of time (temperature is above 393°K). Since the defined penetration depth of coal at a frequency of 2.45 GHz is about 11 cm [23], the size of the heated wall is desirable.

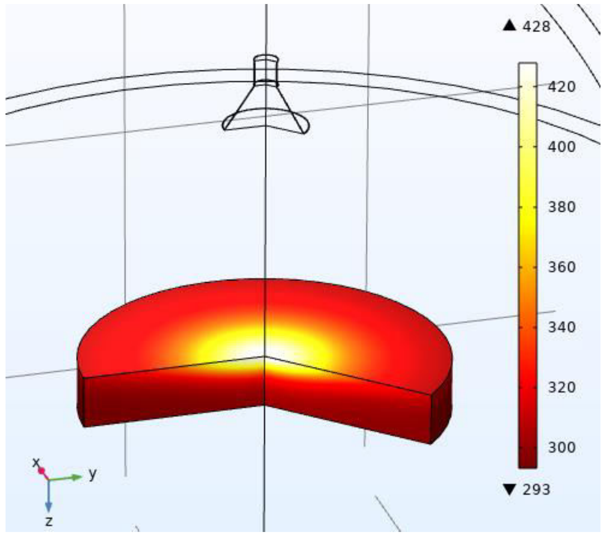


Figure 6. Temperature increase in the coal wall (Temperature in Kelvin).

6. Implementation and Validation

In the previous section, the required antenna to heat coal was designed and simulated. In this section, the body and internal structure of the device are examined to generate a 2.45 GHz wave and send the wave into the waveguide. This device is very simple and includes a high voltage transformer, high voltage diode (11QBP0237), 1.1 microfarad capacitor 2100 volts, 220 volts fan, and 2.45 GHz magnetron, and the body of the device, antenna, and waveguide are made of 6061-T6 aluminum. The schematic of connecting the parts is given in Figure 7.

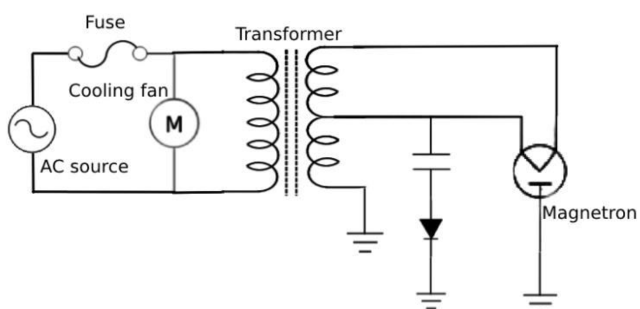
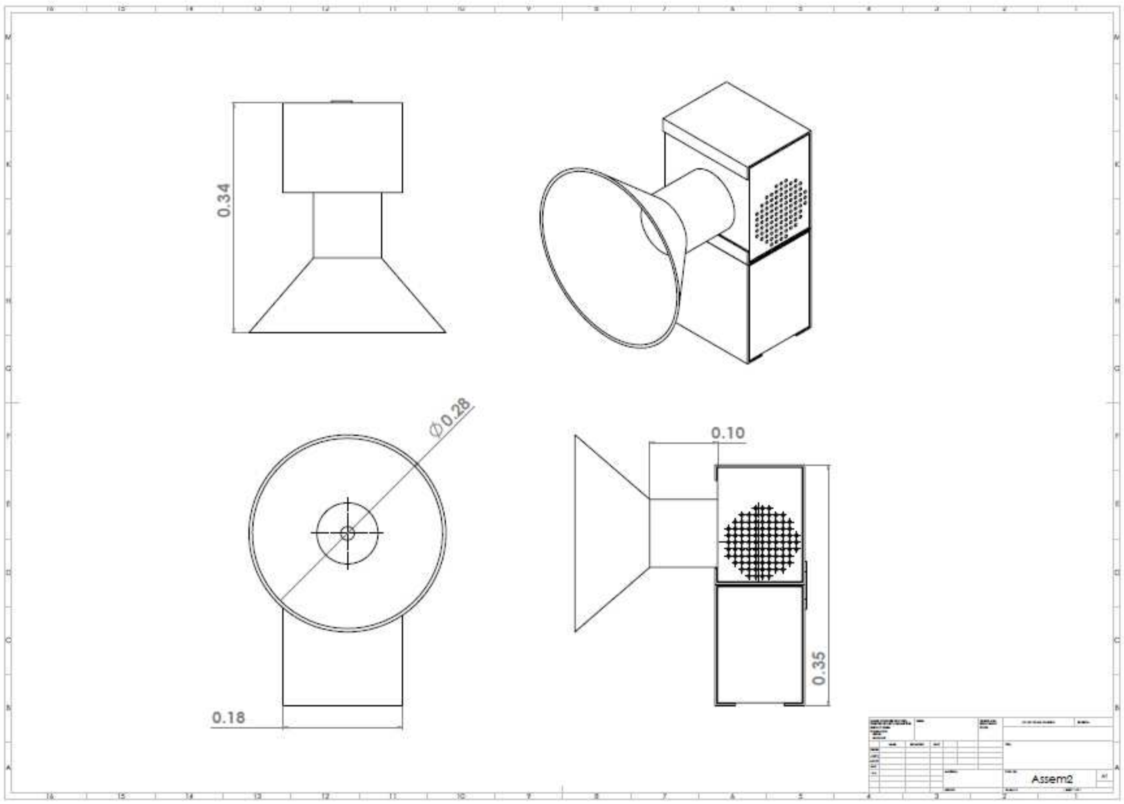


Figure 7. Magnetron connection Diagram [24].

The weight of the device is around 4 kg, which is portable and very light. The main weight of the device is high (most of the system weight is due to the device transformer) due to the iron and copper used in the transformer. According to Figure 8(a), the body is divided into two parts, the generator of radiation and the generator of high voltage, so that the system can be moved easily.



(a)

(b) (c)

Figure 8. a: schematic of the designed device, b: 3D model of the system, c: Implemented device.

A sample of the device is shown in Figure 8(b), and tests related to coal heating are performed using this device.

7. Test

The test is first performed on a small piece of coal in the real environment to show the effect of microwave radiation on the coal. Then a wall of coal is placed in front of the antenna in the real environment as well, and the coal surface temperature is checked after 600, 2000, and 5000 seconds. Figure 10 shows the placement of the coal and the antenna. The distance of the coal sample from the antenna is changed to three distances (10, 50, and 90cm), and the height of the sample from the ground is 20cm. The coal is placed on mica cardboard, which transmits electromagnetic waves well and can also be used in home microwave ovens.

To perform this test, we used a mica plate on the back of the coal to prevent the reflection of microwave radiation, which is transmittent or transparent to microwave radiation, which increases the safety of the tests.

Figure 10. Layout of the designed system, a: Coal sample with a size of 15cm and at a distance of 50cm from the antenna aperture, b: Coal wall at a distance of 90cm from the antenna aperture.

Tables 5 and 6 illustrate the maximum temperature of the coal sample and the coal wall at different time and space intervals. Because the ignition temperature of coal is 360°C, equivalent to 633.15°K, and coal heats up very quickly at a distance of 10 cm, coal was not tested at this distance for 5,000 seconds. At close distances, the coal sample absorbs less energy than the coal wall, and in the same position, the maximum temperature is higher on the surface of the coal wall, but at a distance of 90cm, the coal sample has a higher temperature increase than the coal wall.

Table 5- Maximum temperature of the coal sample with the thickness of the layer of the sample whose temperature is higher than 100°C. The coal sample was measured in 3 distances from the antenna aperture and in three-time intervals in terms of temperature.

	Distance		
Time	10 cm	50 cm	90 cm
600s	405°K Thickness 15 mm	337°K	314°K
2000s	619°K Thickness 50 mm	420°K Thickness 20 mm	356°K
5000s	-	571°K Thickness 70 mm	434°K Thickness 50 mm

Table 6- Maximum temperature of the coal wall with the diameter and thickness of a layer of the sample whose temperature is higher than 100°C. Coal is measured in terms of temperature at three distances from the antenna aperture and at three intervals.

	Distance		
Time	10 cm	50 cm	90 cm
600s	431°K Diameter 28 cm Thickness 18 mm	338°K	313°K

2000s	-	428°K Diameter 29 cm Thickness 20 mm	354°K
5000s	-	591°K Diameter 60 cm Thickness 60 mm	428°K Diameter 40 cm Thickness 50 mm

The results show that by closer the antenna distance to the coal, it is possible to increase the coal temperature in a very short period of time. Also, a more uniform temperature field in a larger radius of the coal can be obtained by distancing the antenna from the coal. Because the ignition temperature of coal powder is lower than that of coal itself, to reduce the chemical reaction in the coal, a sudden rise in temperature and temperatures above 450 K is not recommended in coal. Therefore, this device has the ability to heat coal and evaporate the moisture inside it at the right time without burning the coal surface and to achieve the desired results, only by changing the distance and time of irradiation, the amount of scattering and penetration of the electric field and consequently the size of the temperature field can be changed. Therefore, this proposed system can be a suitable model for conducting preliminary tests to design a methane gas extraction device inside coal mines.

8. Conclusion

Coalbed methane is one of the most valuable extractives in mines, one of the most dangerous flammable and explosive agents in coal mines. Therefore, it is necessary to extract methane gas before and during coal mining operations to prevent explosions and the dangers of methane accumulation and prevent environmental pollution. One of the newest methods of extracting methane gas in coal is the use of microwaves.

In previous studies, tests have been performed in vitro using home and industrial microwave ovens without designing the required device, which has disadvantages such as smal size of the sample inside the chamber, ignoring the ignition temperature of coal or replacing nitrogen or argon gas with air, portability of the device, and inefficiency of the device, which increases the error of the results and reduces their reliability. For this purpose, in this article, we have designed and built a portable microwave gun for heating coal and performed the tests in real conditions. This device consists of a magnetron as a microwave source, a magnetron cooling fan, a high voltage transformer, and a conical horn antenna. The results show that according to the reflection of microwave waves by coal, the distance of coal from the antenna and the size of coal is effective in increasing the temperature of coal, the penetration of waves in coal, and the scattering (uniformity) of electric field and heat. Also, by designing a suitable antenna, it is possible to prevent the reflection of waves around. Therefore, by using this device in coal mines, by controlling the distance from the coal wall and controlling the irradiation time, a controlled heat field can be created inside the coal in addition to extracting methane gar inside the coal, increase the safety factor of the device and prevent explosions or fires in the mines.

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Declaration Conflict of interest

The authors declare that they have no conflict of interest

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