

Innovative Microwave System for Safe and Efficient Coalbed Methane Extraction: Design, Implementation, and Field Applications

Ali Jebelli^{1,*}, Nafiseh Lotfi¹, Maral Partovibakhsh², Arezoo Mahabadi³,
Mohammad Saeid Zare⁴, Mustapha C. E. Yagoub^{5,*}

¹Department of Engineering and Design, Robotic Century Inc, Alberta, Canada

²Department of Engineering, Azad University, Tehran, Iran

³Department of Basic Engineering Science, Tehran University, Tehran, Iran

⁴Faculty of new science and technologies, Tehran University, Tehran, Iran

⁵School of Electrical Engineering and Computer Science, University of Ottawa, Ontario, Canada

*Corresponding author: ali.jebelli@ieee.org

Received August 03, 2024; Revised September 05, 2024; Accepted September 11, 2024

Abstract The escalating global demand for sustainable energy necessitates the maximization of hydrocarbon recovery, with coalbed methane (CBM) representing a crucial yet underutilized resource. However, the low permeability of coal seams and the persistent risk of methane gas explosions present formidable challenges to effective CBM extraction. Traditional mine ventilation systems are often inadequate in managing these risks, highlighting the need for innovative extraction technologies. This research introduces a novel, portable microwave device specifically engineered to enhance coal seam permeability, thereby optimizing CBM recovery while significantly improving safety in coal mining operations. Operating at 2.45 GHz, the device employs a conical horn antenna with a 28 cm aperture to target and evaporate moisture within a 40 cm diameter section of the coal wall, effectively increasing permeability through localized microwave radiation. Our approach addresses critical limitations of previous methodologies, which lacked control over microwave application and operated under non-representative conditions. By simulating and implementing the device under realistic mining environments, we account for the challenges posed by oxygen presence and the coal ignition temperature, ensuring safe operation even in high-risk settings. Extensive field tests corroborate the device's capability to substantially increase methane yield while mitigating explosion hazards. This breakthrough not only marks a significant advancement in CBM extraction technology but also establishes a new paradigm for enhancing safety and efficiency in coal mining. The portability and adaptability of the device further extend its applicability across diverse mining scenarios, positioning it as a pivotal tool in the pursuit of sustainable energy solutions.

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

Cite This Article: Ali Jebelli, Nafiseh Lotfi, Maral Partovibakhsh, Arezoo Mahabadi, Mohammad Saeid Zare, and Mustapha C. E. Yagoub, "Innovative Microwave System for Safe and Efficient Coalbed Methane Extraction: Design, Implementation, and Field Applications." *American Journal of Mining and Metallurgy*, vol. 7, no. 1 (2024): 1-9. doi: 10.12691/ajmm-7-1-1.

1. Introduction

Coalbed methane (CBM) is a natural gas that is adsorbed onto the surface of coal and stored in micropores or natural fractures within the coal [1]. The vast coal resources worldwide present a significant opportunity to extract substantial amounts of methane gas. Recently, in an effort to mitigate environmental concerns, countries have increasingly focused on exploiting coal for clean energy, particularly methane gas [2]. Despite its potential benefits, methane exists in varying concentrations across different ore compositions, with coal typically containing

the highest percentage. This high concentration of methane in coal presents serious risks, including explosions, flaring, and environmental pollution. Often, mine ventilation systems alone are insufficient to effectively dissipate this gas [3,4]. Therefore, the extraction of methane gas from coal seams, both before and during coal mining, is crucial and is largely dependent on the permeability of the coal.

Permeability is a critical property of rocks that indicates their ability to transmit fluids (gas or liquid), and it is influenced by the pressure within the study environment. Permeability is a component of the proportionality constant in Darcy's law, which relates the flow rate to the physical properties of a fluid, such as its viscosity. The

standard unit of permeability is square meters (m^2) in the SI system, and it is commonly measured in darcies (d) or millidarcies (md) in applied contexts ($1\text{d} = 10^{-12} \text{m}^2$) [5]. Darcy first described the process of water flow through sand filters for drinking water. To enhance permeability and flow in rocks—especially in dense, compact, or non-porous formations—artificial methods such as physical fracturing or chemical acidification are often employed.

Due to the potential negative environmental impacts of hydraulic fracturing, this method has been prohibited in some countries. As an alternative, the use of microwave heating to crack the coal surface has been proposed [6]. Microwave radiation has found extensive applications in coal processing, including drying, coking, pyrolysis, flotation, enhancing grindability, and magnetic removal [7,8].

In prior studies, experimental setups often involved filling the chamber with argon or nitrogen to prevent ignition, a condition that differs significantly from actual mining environments [9,10]. This paper tests and simulates various parameters affecting the electric field and heat generation in real mining conditions. Ultimately, we developed a device tailored to these conditions for the extraction of methane gas from coal within mines, taking into account the coal ignition temperature and the relevant parameters. Previous studies have used small controlled cavities for heating coal to manage ignition temperatures [3,5,9,11,12], but such experiments are not feasible under actual mining conditions. Furthermore, the risk of methane gas explosions, along with the potential for human and financial losses and environmental damage, underscores the importance of extracting methane gas before or during coal mining—an approach that previous methods did not sufficiently address.

In summary, this paper presents a groundbreaking approach to CBM extraction, offering a safer, more efficient, and environmentally sustainable method for harnessing this critical energy resource. The subsequent sections of this paper are organized as follows: Section 2 discusses the theoretical foundations of microwave propagation and heat transfer within coal. Section 3 details

the system design of the microwave extraction technology. Section 4 outlines the methodology used to test and validate our theoretical models. Section 5 presents the simulation results predicting system behavior under operational conditions. Section 6 describes the implementation and validation of the system in actual mining environments. Section 7 details the empirical tests conducted to assess the functionality and safety of the system. Finally, Section 8 concludes the paper with a summary of findings and their implications, followed by acknowledgments in Section 9.

2. Theory

To effectively enhance the extraction of coalbed methane using microwave technology, it is crucial to understand the underlying principles governing microwave propagation and heat transfer within the extraction chamber. This section delves into the theoretical aspects necessary for modeling these phenomena, which are essential for optimizing the design and functionality of our microwave extraction system. By examining the propagation of microwaves and their interactions with coal, alongside the mechanisms of heat transfer within the chamber, we aim to precisely calculate the amount of heat absorption and its subsequent transfer throughout the microwave chamber. This theoretical foundation not only informs the engineering design but also ensures that the application of microwave radiation is both efficient and safe, maximizing permeability enhancement while minimizing the risk of ignition. This understanding is vital for developing a controlled and effective method to increase the coal's ability to release methane, thereby facilitating a more sustainable extraction process.

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/m ²)	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/m ³)	velocity vector of translational motion(m/s)
Symbol	μ_r	ϵ_r	T	Q	u
Name	density (kg/m ³)	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/m ³)	diffusivity (diffusion coefficient) (m ² /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_{t_c}	L	f_c	C_0
Name	moisture conductivity	Dynamic viscosity of the fluid kg/m.s	mass transfer coefficient	Aperture efficiency	Antenna gain
Symbol	k_m	ν	k_c	e_A	G
Name	the slant length of the cone from the apex	Diameter of aperture of antenna	Flare angle of antenna	Scattering parameter	
Symbol	L_a	d	θ	S11	

In this paper, ∇ is the gradient, $\nabla \cdot$ is divergence and $\nabla \times$ denotes the curl operator.

2.2. Maxwell Equation

The Maxwell equation governing electromagnetic waves inside a microwave oven is as follows [13]:

$$\nabla \times \mu_r^{-1} (\nabla \times E) - k_0^2 \left(\epsilon_r - \frac{j\sigma}{\omega\epsilon_0} \right) E = 0 \quad (1)$$

In which the permeability coefficient of the vacuum or air magnetic field is $4\pi \times 10^{-7} \text{ H/m}$ and the permeability coefficient of the vacuum or air electric field is $8.854 \times 10^{-12} \text{ Farad/m}$ [14,15,16].

2.3. Heat Transfer

Heat transfer in materials occurs through conduction, convection, and radiation. In liquids, heat is often transferred by convection, where the movement of the liquid itself carries heat from one location to another. Another method of heat transfer is conduction, where there is no movement of matter; instead, energy is transferred within the substance through direct contact with another substance. The third method, radiation, involves the transfer of energy through the absorption or emission of electromagnetic waves. The increase in temperature within a non-uniform isotropic medium can be determined by solving the following equation [17]:

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

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

$$q = q_{rad} + q_{cond} \quad (3)$$

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:

$$q_{cond} = -k \cdot \nabla T \quad (4)$$

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).

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

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

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

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

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. TE₁₁ emission mode is considered for cylindrical waveguide [18].

2.5. Boundary Conditions

The impedance boundary condition is considered for antenna and waveguide walls, the governing relationship of which is as follows [14,15]:

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

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

$$-n \cdot q = \Delta T^* \left\{ \begin{array}{l} \left[\frac{k}{L} \left(0.68 + \frac{0.67 Ra_L^{1/4}}{\left(1 + \left(\frac{0.492k}{\nu C_p} \right)^{9/16} \right)^{4/9}} \right) \right] \text{ if } Ra_L \leq 10^9 \\ \left[\frac{k}{L} \left(0.825 + \frac{0.387 Ra_L^{1/4}}{\left(1 + \left(\frac{0.492k}{\nu C_p} \right)^{9/16} \right)^{8/27}} \right) \right]^2 \text{ if } Ra_L > 10^9 \end{array} \right. \quad (8)$$

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) [19].

3. System Design

The system design of the microwave-based coalbed methane extraction device is a critical aspect of ensuring effective and efficient operation in real-world mining environments. This section outlines the key components involved in the system's design, focusing on the waveguide and antenna, which play essential roles in the propagation and delivery of microwave energy to the coal seam.

3.2. 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:

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

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

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

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

3.1. 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 [20]:

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

The gain of the conical horn antenna is also calculated as follows [20]:

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

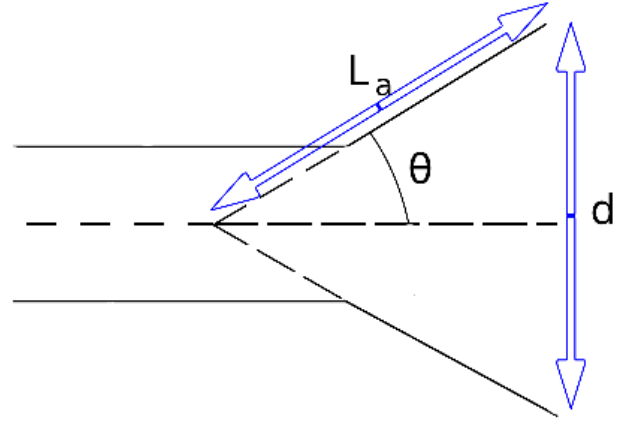


Figure 1. Conical antenna with aperture diameter d and flare angle $= \theta$

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:

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

$$\rightarrow \text{radius} = 0.043m$$

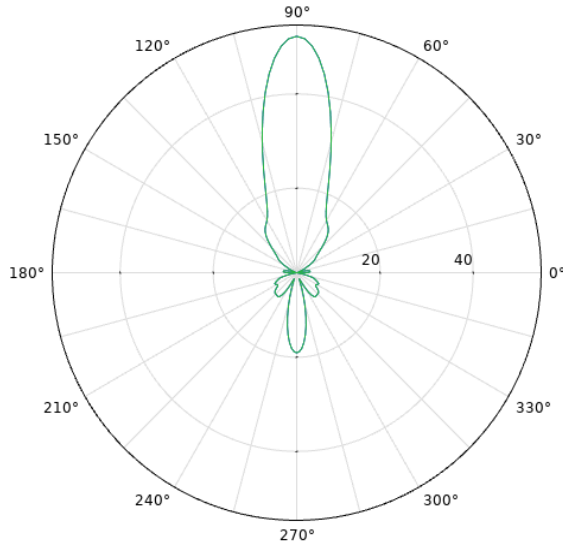
If the flare angle of the antenna is 35 degrees, the dimensions of the antenna are as follows:

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

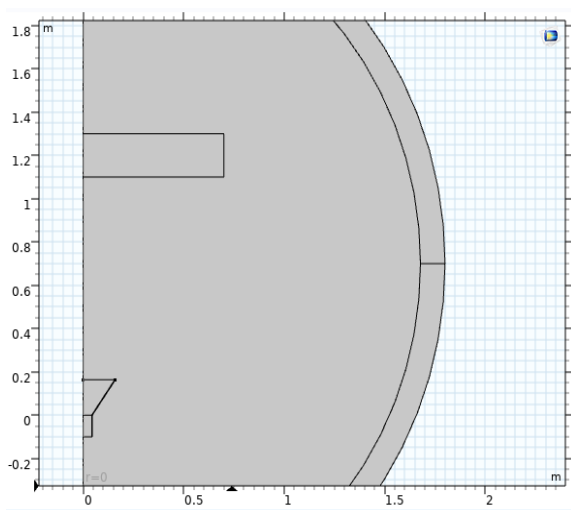
The radiation pattern of the desired antenna is obtained by using simulation in COMSOL. Figure 2 shows the simulated radiation patterns of the proposed antenna. The maximum antenna gain is 16.81 dBi, and its s_{11} is -23.2dB, which is desirable [21, 22]. The maximum aperture efficiency is 92%, according to the antenna size and operating frequency.

Table 3. Antenna sizes and their waveguid.

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]

**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**

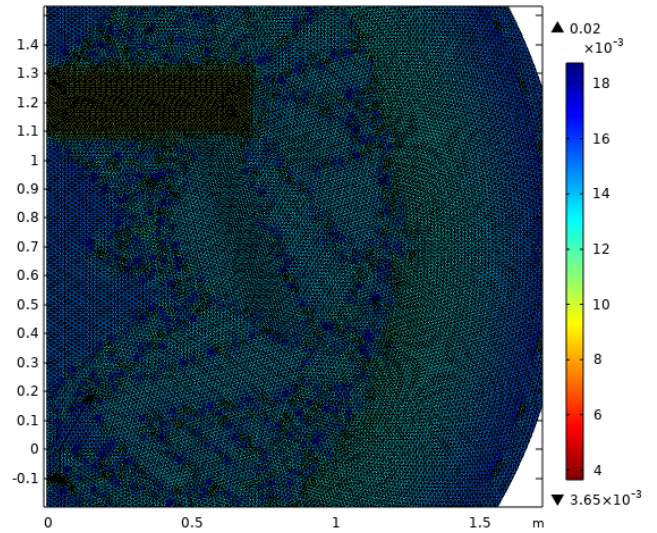
4.2. Mesh Quality

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.

Table 4. Specifications of materials at 293.15 K [23]

Name	Units	Coal	aluminum 6061-T6	Air
Relative permittivity(ϵ' - $\epsilon''j$)	-	2.882-0.301j	1	1
Relative permeability(μ' - $\mu''j$)	-	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

**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 [6,7,8,9,10,11,12]. 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.

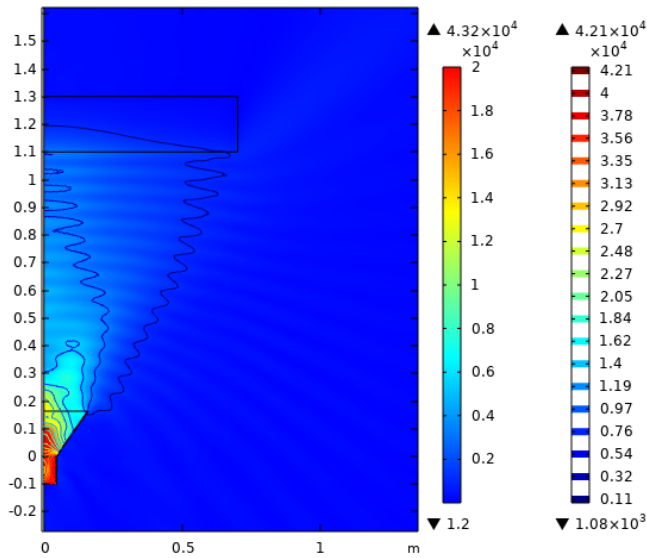


Figure 5. Scattering of the electric field radiated from the antenna to the coal wall. The maximum field occurs at 4.32×10^4 V/m inside the waveguide

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 [24], the size of the heated wall is desirable.

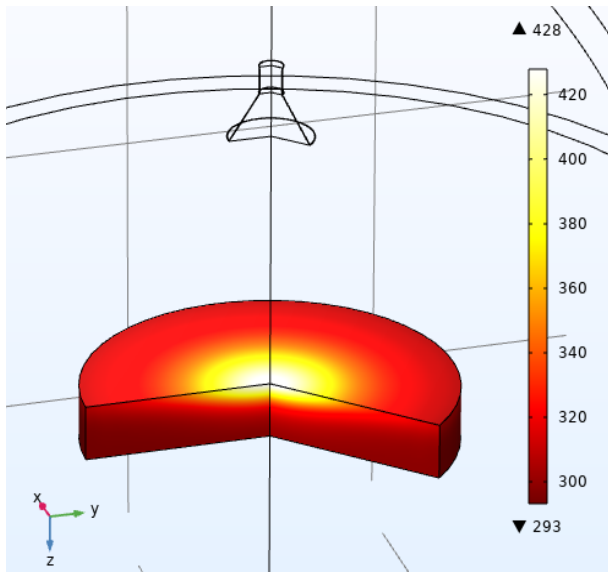


Figure 6. Temperature increase in the coal wall (Temperature in Kelvin)

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.

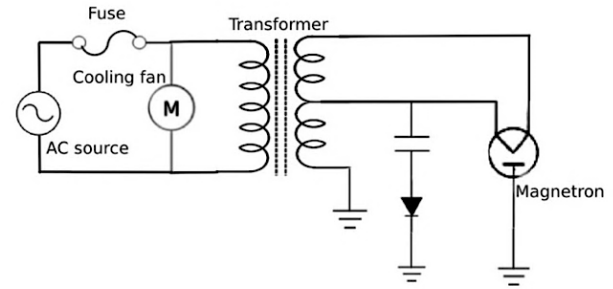
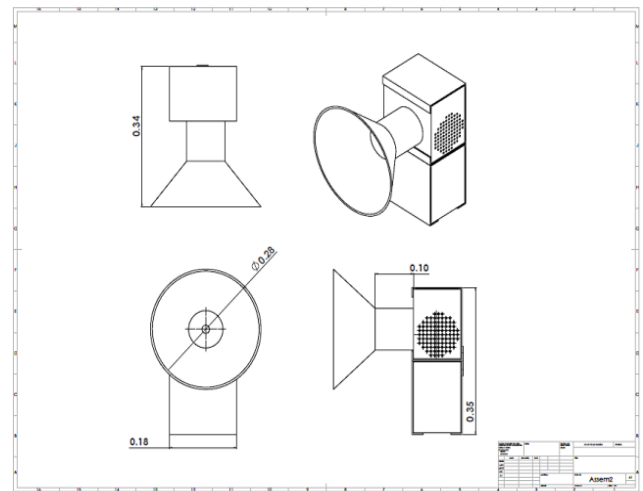


Figure 7. Magnetron connection Diagram [25]

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



(a)



(b)



(c)

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

7. Tests

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 9 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.



(a)



(b)

Figure 9. 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

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

Time	Distance		
	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

Time	Distance		
	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

Table 5 and Table 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.

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 (CBM) is a valuable energy resource extracted from coal mines, but it also poses significant dangers due to its highly flammable and explosive nature. To prevent explosions, mitigate the risks associated with methane accumulation, and reduce environmental pollution, it is crucial to extract methane gas both before and during coal mining operations. One of the most innovative methods for achieving this is through the application of microwave technology.

Previous studies have largely relied on in vitro experiments using household and industrial microwave ovens, which were not specifically designed for this purpose. These approaches had several limitations, including small sample sizes, disregard for the coal's ignition temperature, substitution of air with inert gases like nitrogen or argon, lack of portability, and overall inefficiency. These factors contributed to increased error margins and reduced reliability of the results.

In this study, we have designed and constructed a portable microwave gun specifically tailored for heating coal and conducted tests under real-world mining conditions. This device includes a magnetron as the microwave source, a cooling fan for the magnetron, a high-voltage transformer, and a conical horn antenna. Our results demonstrate that factors such as the reflection of microwave waves by coal, the distance between the coal and the antenna, and the size of the coal significantly influence the increase in coal temperature, the penetration depth of the waves, and the uniformity of the electric field and heat distribution. Additionally, by designing an appropriate antenna, it is possible to minimize wave reflection and optimize energy delivery.

By employing this device in coal mines, and by carefully controlling the distance from the coal wall and the duration of microwave irradiation, it is possible to create a controlled heat field within the coal. This not only facilitates the extraction of methane gas but also enhances operational

safety by preventing explosions and fires within the mines.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to everyone who contributed to this research. We extend special thanks to Robotic Century Inc for their support and for providing access to their facilities and laboratories under the terms of our contract, which were essential to the successful completion of this project.

References

- [1] K. Hanushevych, V. Srivastava, "Coalbed Methane: Places of Origin, Perspectives of Extraction, Alternative Methods of Transportation with the Use of Gas Hydrate and Nanotechnologies," *Mining of mineral deposits*, 11(3), pp. 23-33, 2017.
- [2] R. M. Flores, "Coal and Coalbed Gas," 1st Edition, Elsevier, 2014
- [3] Z. Wang, Xi. Wang, "Promotion Effects of Microwave Heating on Coalbed Methane Desorption Compared with Conductive Heating," *Scientific Reports*, 11, 9618, 2021.
- [4] A. Jafarpour, M. Najafi, "Evaluating the Criteria Affecting Methane Drainage in Underground Coal Mines Using Interpretive Structural Modeling," *Journal of Mineral Resources Engineering*, 4(4), pp. 59-79, 2020.
- [5] Y. Ma, Y. Cheng, W. Shang, D. Zhao, and Xi. Duan, "Experimental Study on Coal Permeability Variation during Microwave Radiation," *Advances in Materials Science and Engineering*, 2020.
- [6] A. Jebelli, Ali; A. Mahabadi, Arezoo, R. Ahmad, "Numerical Simulation and Optimization of Microwave Heating Effect on Coal Seam Permeability Enhancement," *Technologies*, 10(70), 2022.
- [7] J. Huang, G. Xu, Y. Chen, Z. Chen, "Simulation of Microwave's Heating Effect on Coal Seam Permeability Enhancement," *International Journal of Mining Science and Technology*, 29(5), pp. 785-789, 2019.
- [8] E. Binner, E. Lester, S. Kingman, Ch. Dodds, J. Robinson, T. Wu, P. Wardle, and J. P. Mathews, "A Review of Microwave Coal Processing," *Journal of Microwave Power and Electromagnetic Energy*, 48(1), pp. 35-60, 2014.
- [9] B. Lin, H. Li, Zh. Chen, Ch. Zheng, Y. Hong, and Zh. Wang, "Sensitivity Analysis on the Microwave Heating of Coal: A coupled electromagnetic and heat transfer model," *Applied Thermal Engineering*, vol. 126, pp. 949-962, 2017.
- [10] Zh. Peng, Xi. Lin, Zh. Li, J. Y. Hwang, B. G. Kim, Y. Zhang, G. Li, and T. Jiang, "Dielectric Characterization of Indonesian Low-Rank Coal for Microwave Processing," *Fuel Processing Technology*, vol. 156, pp. 171-177, 2017.
- [11] H. Li, L. Tian, B. Huang, J. Lu, Sh. Shi, Y. Lu, F. Huang, Y. Liu, and Xi. Zhu, "Experimental Study on Coal Damage Subjected to Microwave Heating," *Rock Mechanics and Rock Engineering*, vol. 53, pp. 5631-5640, 2020.
- [12] Z. Wang, Xi. Ma, J. Wei, and N. Li, "Microwave Irradiation's Effect on Promoting Coalbed Methane Desorption and Analysis of Desorption Kinetics," *Fuel*, vol. 222, pp. 56-63, 2018.
- [13] B. Lin, H. Li, Zh. Chen, Ch. Zheng, Y. Hong, and Zh. Wang, "Sensitivity Analysis on the Microwave Heating of Coal: A coupled Electromagnetic and Heat Transfer Model," *Applied Thermal Engineering*, vol. 126, pp. 949-962, 2017.
- [14] D. M. Pozar, "Microwave Engineering" Fourth Edition, Wiley, 2011.
- [15] A. Jebelli, A. Mahabadi, M.C. E. Yagoub, and H. Chaoui, "Magnetic Force Calculation between Magnets and Coils," *International Journal of Physics*, 8(2), pp. 71-80, 2020.
- [16] A. Jebelli, A. Mahabadi, H. Chaoui, and M. C. E. Yagoub, "Simulation of Magnetic Force between Two Coaxial Coils with Air Core and Uniform Flow in MATLAB," *International Journal of Physics*, 9(4), pp. 186-196, 2021.
- [17] F. Ghalichia, S. Behniab, and E. Sadighrad, "Calculations for Ultrasonic Transducer Design and Temperature Tracking for Hyperthermia in Cervical Cancer," *Iranian Conference on Biomedical Engineering*, 2003.
- [18] M. Mitrović and B. Jokanović, "Field Tunneling and Losses in Narrow

- Waveguide Channel," *Microwave Review* 16(2), pp. 8-13, 2010.
- [19] D.V. Miroshnichenko, I. V. Shulga, Yu. S. Kaftan, N. A. Desna, and Yu. V. Nikolaichuk, "Ignition Temperature of Coal 3. Multicomponent coal mixtures," *Coke Chemistry*, vol. 60, pp. 343-347, 2017.
- [20] N. A. Aboserwal, C. A. Balanis, and C. R. Birtcher, "Conical Horn: Gain and Amplitude Patterns," *IEEE Transactions on Antennas and Propagation*, 6(7), pp. 3427-3433, 2013.
- [21] P. Duangtang, P. Mesawad, and R. Wongsan, "Gain Improvement of Conical Horn Antennas by Adding Wire Medium Structure," 13th International Conference on Electrical Engineering/ Electronics, Computer, Telecommunications, and Information Technology (ECTI-CON), pp. 1-5, 2016.
- [22] P. Duangtang and R. Wongsan, "Wire Medium Structure for Gain Enhancement of Conical Horn Antenna," *International Electrical Engineering Congress (iEECON)*, pp. 1-4, 2018.
- [23] J. R. Davis, "Aluminum and Aluminum Alloys," *ASM specialty handbook*, ASM International, 1993.
- [24] E. Binner, M. M. Munoyerro, T. Huddle, S. Kingman, Ch. Dodds, G. Dimitrakis, J. Robinson, and E. Lester, "Factors Affecting the Microwave Cooking of Coals and the Implications on Microwave Cavity Design," *Fuel Processing Technology*, vol. 125, pp. 8-17, 2014.
- [25] W. Choe, G. Kwon, J. Kim, J. Kim, S. Jeon, and S. Huh, "Simple Microwave Preionization Source for Ohmic Plasmas," *Review of Scientific Instruments*, 71(7), pp. 2728-2732, 2000.



© The Author(s) 2024. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).