RESEARCH ARTICLE

The release of nicotine and aromatic compounds from pyrolysis of tobacco waste based on the field synergy principle

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Tobacco waste is a valuable resource, capable of producing organic compounds like nicotine and aromatic substances through pyrolysis, which hold significant potential for waste applications. This study investigated the mechanisms behind the release of nicotine and aromatic compounds during tobacco waste pyrolysis by applying the concept of field synergy. By combining experimental analysis with theoretical simulation, factors such as pyrolysis temperature and gas fluidization rate affected the release of these compounds were investigated. The study also measured nicotine and aromatic compound contents in high-value products derived from tobacco waste using gas chromatography-mass spectrometry (GC/MS). Tobacco waste was pyrolyzed in a fluidized bed reactor, and the resulting gases, solids, and liquids were analyzed. Numerical simulations using ANSYS FLUENT were performed to explore the relationship between the synergistic angle α of temperature and velocity gradients within the pyrolysis pipe and the resulting products. The results showed that nicotine content reached its peak at 450°C. As the temperature increased, the macromolecules in tobacco waste broke down into smaller molecules, which increased the production of compounds, though their relative levels decreased. GC/MS analysis identified nicotine, p-methylphenol, 3-cyanopyridine, quinoline, cinnamonitrile, and phenol as the major components of the pyrolysis bio-oil from tobacco waste. Additionally, calculations of α under different conditions indicated that 450°C was the optimal temperature for obtaining nicotine and aromatic compounds with temperature variations having minimal impact. This study provided a robust theoretical and experimental basis for the efficient utilization of tobacco waste, which was essential for advancing green energy and chemical industries.

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Introduction

The production and consumption of tobacco products generate significant amounts of waste including cigarette butts, tobacco dust, and filter residues. These wastes contain harmful substances like nicotine and tar that contribute to environmental pollution. Pyrolysis technology offers an effective way to break down these harmful components, thereby reducing their environmental impact. Pyrolysis is a process that transforms organic substances into gases, liquids, and solid products under anaerobic or low oxygen conditions. When applied to tobacco waste, pyrolysis can produce gases like hydrogen and carbon monoxide, liquid fuels like bio-oil, and high-quality carbon materials like activated carbon, all of which have potential energy

applications. These products are commercially viable and can be utilized in various scenarios. Nicotine and aromatic compounds generated from the pyrolysis of tobacco waste have numerous applications. Therefore, pyrolyzing tobacco waste not only enables the recycling of resources, reducing reliance on fossil energy, and lowering greenhouse gas emissions, but also provides raw materials for various industries, offering significant economic and environmental benefits [1]. In the past, tobacco waste was typically landfilled or incinerated [2], which squandered resources and harmed environment. To fully utilize tobacco waste, the priority is to treat it in a way that eliminates harm and maximizes resource reuse [3], while achieving the effect of recycling, turning waste into treasure [4]. Pyrolysis offers a viable solution for turning tobacco waste into valuable products treasure, extracting high-value compounds like nicotine from pyrolysis oil [5]. Additionally, the CO, CO_2, and other gases produced during pyrolysis can be used for energy production and as chemical raw feedstocks.

In addition to producing nicotine, pyrolysis also generates a significant number of aromatic compounds such as chlorogenic acid, chlorohydrin, and limonene [6]. These compounds not only influence the flavor of cigarettes but also have applications in the medical, chemical, and agricultural industries [7]. Recent research suggests that chlorogenic acid can regulate autophagy by inhibiting Alkbh5 demethylase activity, thereby improving hepatic steatosis [8]. Additionally, the combined effects of chlorophyllin and carnauba wax can enhance the hydrophobicity and mildew resistance of bamboo [9]. In agriculture, limonene exhibits antifungal properties against *Candida parapsilosis* and can serve as a preventive agent against viruses [10]. Xia *et al*. studied tobacco pyrolysis oil samples produced at various temperatures in a fluidized bed pyrolysis unit and found that the oil obtained at 400°C was ideal for preparing essential oils for e-cigarettes, providing the best smoking experience [11]. Yoshida *et al*. explored the formation of polycyclic aromatic

amines from amino acids during tobacco pyrolysis and discovered that aromatic structure in the side chain of phenylalanine contributed aryl carbon sources crucial for the formation of aminobiphenyls, but not for aminonaphthalene [12].

Tobacco's complex composition results in a wide variety of products during pyrolysis, requiring detailed analysis and characterization due to the numerous physical and chemical reactions involved. The key factors influencing the pyrolysis products include the pyrolysis temperature, the rate of temperature increase, the duration of pyrolysis, and the flow rate of fluidized gases [13-15]. Temperature is one of the most crucial parameters in the pyrolysis process, as it directly influences the breakdown of compounds in tobacco waste and determines the types of compounds produced. The rate of temperature increase affects both the duration of the pyrolysis reaction and the reaction kinetics of the substances being pyrolyzed. Rapid heating typically results in the production of more light compounds, while slower heating tends to produce more deposits and heavy compounds [16]. The duration of pyrolysis also impacts the final product composition with longer pyrolysis times promoting a more complete cracking reaction but leading to secondary reactions such as polymerization or gasification, which can alter the distribution of the final products [17]. When pyrolysis is conducted using a fluidized bed reactor, the gas flow rate significantly influences material agitation and efficiency of heat and mass transfer. An optimal flow rate can enhance these efficiencies and minimize localized overheating or overcooling, which, in turn, affects the quality and quantity of pyrolysis products [18]. Pyrolysis is typically performed in an inert atmosphere such as nitrogen or carbon dioxide to prevent oxidative reactions with different atmospheric conditions leading to varied pyrolysis pathways and products [19]. Additionally, the particle size and surface area of the material pyrolyzed impacts its pyrolysis kinetics with smaller particle achieving more efficient and uniform heating [20]. From a

thermodynamic perspective, heat transfer indirectly influences the products of pyrolysis [21]. The principle of field synergy, derived from the interaction between the temperature field and velocity field, provides a robust evaluation method for assessing the heat transfer efficiency of the heater [22]. By applying this principle, a detailed analysis of pyrolysis products is conducted. Furthermore, the parameter control strategy for the tobacco pyrolysis heater pipe is informed by insights into the temperature and velocity fields, offering valuable guidance.

This study aimed to analyze the products of pyrolysis using tobacco waste and explore the optimal operating conditions by applying the field synergy principle. Pyrolysis was conducted using a fluidized bed reaction system to investigate the influence of pyrolysis temperature on the yield and composition of bio-oil derived from tobacco waste. By studying the release of nicotine and aromatic compounds during pyrolysis, the reaction conditions could be optimized using the field synergy principle to enhance the yield and quality of the products. Adjusting the parameters such as temperature, fluidized gas flow rate, and reaction time could maximize the yield of nicotine and aromatic compounds, which provided a theoretical foundation and technical support for the resource utilization of tobacco waste and promoted the development of green energy and chemical industry.

Materials and methods

Raw materials

Tobacco waste sourced from Hongta Group in Yuxi, Yunnan, China was screened and cleaned to remove non-biomass impurities. The samples were ground into fine particles ranging from 0.1 to 0.5 mm, which would promote uniform heat transfer and accelerate the pyrolysis reaction. Natural moisture in the tobacco waste could negatively impact pyrolysis efficiency and heat energy utilization. Therefore, the waste was dried in a constant-temperature dryer at 70°C for 6 hours, reducing the moisture content to below 10%, which could improve the quality of pyrolysis oil and increase gas product yields. Preheating the tobacco waste before feeding it into the pyrolysis reactor minimized heat loss and accelerated the start-up of the pyrolysis process.

Fluidized bed pyrolysis

Tobacco pyrolysis can be categorized into two main types including dry pyrolysis and wet pyrolysis. This study focused on dry pyrolysis, which involved drying and decomposing tobacco at high temperatures. The studies were conducted using a fluidized bed system with a feed rate of 10 kg/h. The system included a nitrogen storage tank with 99.9% purity, a tubular pyrolysis furnace, an LTD programmable temperature controller, a constant-temperature condenser, a PC for monitoring, and an exhaust gas treatment device containing 80% H_2SO_4 solution, 10% NaOH solution, and water (Figure 1). The temperature and nitrogen flow rate were programmed and controlled *via* the computer. The temperature was increased at a rate of 6~8°C per minute, and the final temperature was maintained for 120 minutes to ensure complete pyrolysis of materials. The experimental temperature range was between 200 and 600°C with a condensation temperature at 5°C and the gas fluidization velocity as 0.15 - 0.8 m/s. The heating pipe in the tubular pyrolysis furnace was made of quartz glass with 1,000 mm in length, 72 mm of inner diameter, and 80 mm of outer diameter. A 5 mm-thick sand core was positioned 400 mm from the bottom of the pipe with a pore grade of G0. This setup ensured that the gas generated by pyrolysis could pass through the sand core, which held the tobacco particles being pyrolyzed at its top. Pyrolysis gas and nitrogen entered the pipe from the top of 20 mm above the bottom. The gas exited to a condenser for condensation. Non-condensable gas was processed through an exhaust gas treatment system to ensure that it was harmless before being collected for use. The fluidized bed pyrolysis furnace and heating pipe used in this study was manufactured by Chengdu Guoguang Electric Co., Ltd., Chengdu, Sichuan, China.
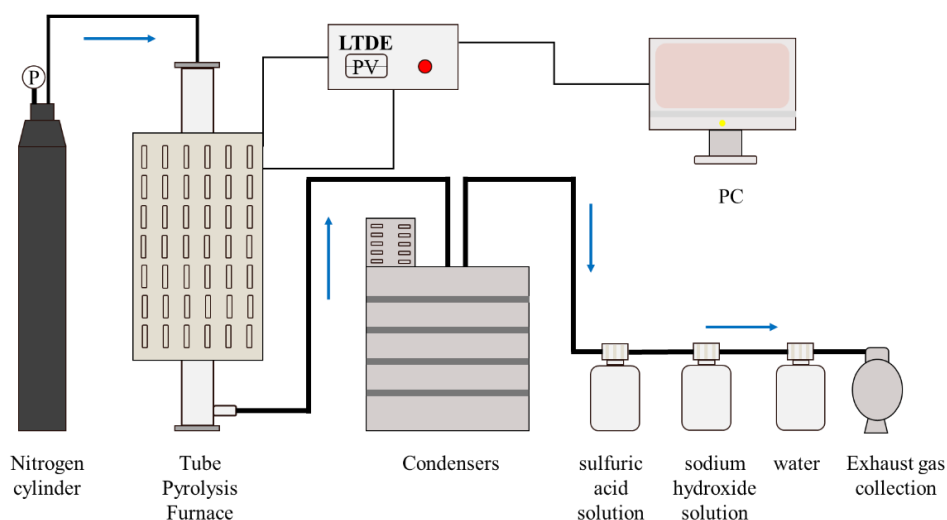
Figure 1. Experimental setup of tobacco pyrolysis.

Characterization and analysis

The bio-oil produced from pyrolysis was analyzed for aroma compounds and nicotine using an Agilent 8890 GC System-5977B GC/MSD Gas Chromatograph-Mass spectrometer (Agilent, Santa Clara, CA, USA) with a Solid Phase Microextraction (SPME) injection head, an Agitator shaker, and a DVB/CWR/PDMS adsorption head. The HP-INNOWax (60 m × 250 μm × 0.25 μm) chromatographic column was used in this research. The oven temperature was initially set to 70°C. The adsorption head had a 40-minute adsorption time, and the GC cycle lasted for 70 minutes. The inlet temperature of the GC was set to 250°C for aging. The temperature program involved holding at 45°C for 1 minute, ramping to 120°C over 2 minutes at 4°C/min, increasing to 200°C over 2 minutes at 4°C/min, and finally ramping up to 260°C over 9 minutes at 15°C/min. The transfer line temperature was kept at 250°C. For the mass spectrometer, the ion source temperature was set to 230°C with a solvent delay of 9.5 minutes. The ion scan range was from 40 to 450 m/z.

Field synergy principle

During biomass pyrolysis, the heating process requires a significant amount of electrical energy, which leads to substantial resource consumption.

If the energy used in pyrolysis is not effectively converted into the desired target products, the potential benefits of energy savings, emission reductions, and resource recycling cannot be fully realized. Therefore, improving heat transfer efficiency and reducing the energy consumption of the transport fluid are critical. The main challenge lies in enhancing the overall performance of the equipment while addressing the conflict between increased heat transfer and fluid power consumption **Error! Reference source not found.**. The effectiveness of heat transfer directly influences pyrolysis efficiency and, consequently, the production of pyrolysis products. Thus, it is essential to analyze the heat transfer performance of the pyrolysis heating pipe. The heat exchange efficiency was assessed by calculating the velocity field and temperature fields within the heating pipe as shown in equation (1) **Error! Reference source not found.**.

$$\bar{U} \cdot \nabla\bar{T} = |\bar{U}||\nabla\bar{T}|cos\alpha \qquad (1)$$

where, $\bar{U}\ and\ \nabla\bar{T}$ were the velocity vector and temperature gradient vector, respectively. Equation (1) transformed to get the synergy angle between the velocity vector and temperature gradient vector as shown in equation (2).

$$\alpha = arccos \frac{u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}}{\sqrt{u^2+v^2+w^2}\sqrt{\left(\frac{\partial T}{\partial x}\right)^2+\left(\frac{\partial T}{\partial y}\right)^2+\left(\frac{\partial T}{\partial y}\right)^2}} \qquad (2)$$

where the numerator term was the dot product of the velocity vector and the temperature gradient vector. The denominator was the mode of the velocity vector and the mode of the temperature gradient vector, respectively.

Heating pipe model and mesh generation
The heating pipe was simplified for analysis. In the actual experimental, the heating section was 500 mm in length, so this value was used in the numerical simulation. The model was a long cylindrical pipe with an inner diameter of 74 mm and an outer diameter of 80 mm, made of transparent quartz glass, which could safely operate at continuous temperature from 1,000 to 1,100℃. Since the heating pipe had a regular shape, a square grid was used for the simulation with the boundary layers at the inlet and outlet refined. The total number of grids used was 65,625. The initial external temperature was 23°C with nitrogen used as the fluidizing gas. The flow rates were set to 0.15, 0.25, 0.35, and 0.45 m/s, respectively. The outlet was configured as a pressure outlet. The interface between the fluid and the solid was treated as a fluid-solid coupled heat transfer boundary. The outer wall of the quartz glass pipe served as the heat source with constant wall temperatures ranging from 200 to 600°C.

Results and discussion

Fluidized bed pyrolysis
The pyrolysis of tobacco generates a wide range of chemical compounds including phenols, ketones, furans, olefins, esters, and more. The results showed that, between 400~600°C, the main compounds produced were nicotine, p-methylphenol, 3-cyanopyridine, phenol, and isoquinoline (Figure 2). The relative content of nicotine increased and peaked at 450°C, and then

began to decrease after that (Figure 3). This decline occurred because nicotine, a large molecule nitrogen-containing molecule, broke down into various smaller molecules. Nicotine is a primary alkaloid in tobacco, composed of nitrogen, carbon, hydrogen, and other elements, and has a complex ring structure. Under high temperatures, the molecular structure of nicotine tends to break apart, resulting in the formation of smaller molecule substances. High-temperature pyrolysis provides sufficient energy to break the bonds within the nicotine molecule, leading to dissociation and reorganization of the molecular structure [25]. This process results in the formation of small molecules such as ammonia, carbon monoxide, and methane. Additionally, high temperatures cause the macromolecules in tobacco like cellulose, hemicellulose, and lignin to thermally decompose or cleave and enhance reaction activity, making different chemical reactions and rearrangements more likely to occur, forming a wider variety of substances. The primary cleavage products can undergo further secondary reactions or condensation reactions to form new compounds, such as phenols, furans, and aromatic compounds.
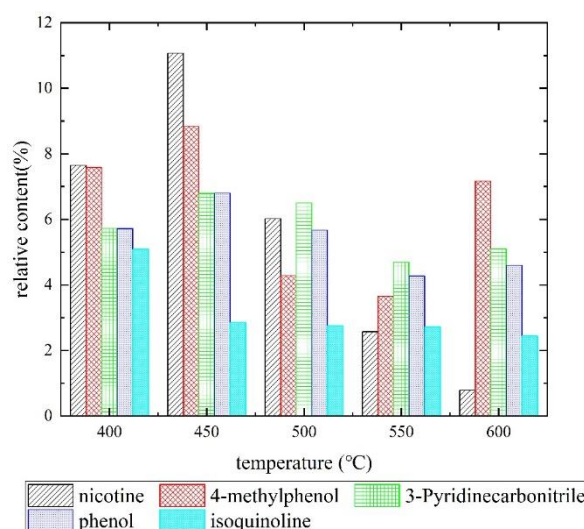

Figure 2. Relative content of pyrolyzed nicotine and major Aromatic compounds in tobacco wastes.
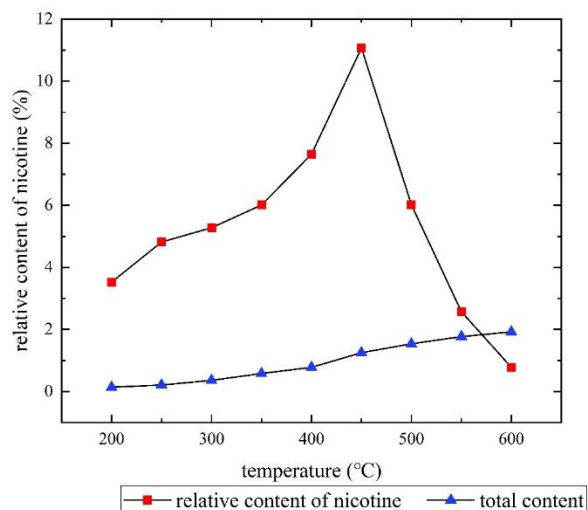
Figure 3. Relative content of nicotine in pyrolyzed tobacco waste at different temperatures.

The results of this study showed that, at higher temperatures, additional compounds like formaldehyde, acrolein, toluene, and xylene were detected although their relative levels were low, which was primarily because nicotine underwent a chemical reaction at high temperatures, where the bonds within its molecule broke, and the atoms rearranged, leading to the formation of other substances. These transformations could result from various chemical reactions such as thermal decomposition, oxidation, reduction, polymerization, which altered the molecular structure of nicotine and ultimately produced new compounds.

Tobacco waste contains hundreds of different substances. The relative contents of compounds at 450℃ and 600℃ were shown in table 1. As the pyrolysis temperature increased, more compounds were released. Some of these compounds were unique to tobacco like nicotine, while others resulted from the decomposition of macromolecules into new compounds. For example, at 450℃, the relative content of nicotine started to decrease as it thermally decomposed into formaldehyde, acrolein, toluene, and other substances. During pyrolysis, the total amount of various compounds increased, but their relative content decreased as the temperature rose. Therefore, lower temperatures were more conducive to the subsequent separation and purification of specific compounds. The rate of the pyrolysis reaction increased with temperature, leading to a faster process. At higher temperatures, the liquid and solid substances in the pyrolysis products evaporated and desorbed, while volatile organic compounds in the pyrolysis exhaust gas were more easily released, resulting in the production of more gaseous products. The results indicated that the highest concentrations of nicotine, p-methylphenol, and phenol were observed at 450°C (Table 1). This temperature was ideal for extracting nicotine and aromatic compounds because nicotine had a boiling point of around 250°C. At this temperature, nicotine and other aromatic substances in the tobacco were released as gases with their concentrations peaking at 450°C. However, at 600℃, the levels of nicotine, p-methylphenol and other compounds were decreased with nicotine dropping to 0.78%.

The yield of pyrolysis oil varied with temperature and nitrogen flow rate (Figure 4). The results showed that, when the temperature exceeded 450℃ and nitrogen flow rate was greater than 0.35 m/s, the yield of pyrolysis oil increased significantly, which was primarily due to the effect of temperature. At higher temperatures, the tobacco waste in the heating pipe underwent carbonization, producing carbon particles, while a small amount of substances was also released. With a higher nitrogen flow rate, these carbon particles were more likely to be carried into the condenser by the nitrogen, leading to notable changes in the quality of pyrolysis oil. Therefore, during pyrolysis, it was crucial to avoid excessively high temperature and gas flow rates. Additionally, heat transfer played a critical role in the quality of pyrolysis oil. The temperature gradient vector reflected the temperature changes inside the heating pipe. A larger temperature gradient speeded up the pyrolysis of tobacco wastes and affected both the type and yield of the pyrolysis products. A steeper
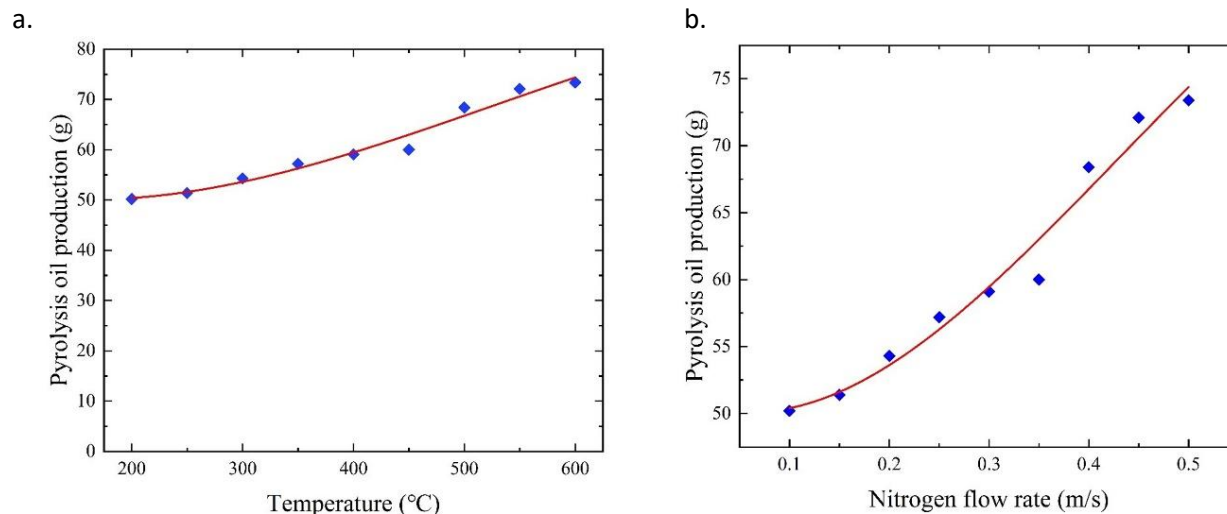
a.

b.

Figure 4. The relationship between pyrolysis oil yield and temperature (a), nitrogen flow rate (b).

Table 1. Comparison of relative compound content (> 0.70%) at 450°C *vs.* 600°C.

450℃		600℃	
Name of compound	**relative content**	**Name of compound**	**relative content**
Nicotine	11.07%	p-Cresol	7.17%
p-Cresol	8.83%	3-Pyridinecarbonitrile	5.10%
Phenol	6.80%	Phenol	4.60%
3-Pyridinecarbonitrile	6.79%	p-Cresol	3.30%
Phenol, 3-ethyl-	3.41%	Phenol, 3-ethyl-	2.69%
Isoquinoline	2.85%	Quinoline	2.64%
Ethanone, 1-(3-pyridinyl)-	2.77%	1H-Isoindole-1,3(2H)-dione, 2-methyl-	2.63%
Quinoline	2.64%	Pyridine, 3-phenyl-	2.60%
1,3-Dicyanobenzene	2.41%	Ethanone, 1-(3-pyridinyl)-	2.49%
Pyridine, 3-(3,4-dihydro-2H-pyrrol-5-yl)-	2.40%	Isoquinoline	2.44%
2,3'-Dipyridyl	2.29%	Pyridine, 4-ethenyl-	2.25%
2-Propenenitrile, 3-phenyl-, (E)-	2.25%	Ethanone, 1-(2-methylphenyl)-	2.23%
Pyridine, 3-phenyl-	2.16%	2-Propenenitrile, 3-phenyl-, (E)-	1.96%
Phenol, 2-methoxy-	2.11%	3-Pyridinecarboxaldehyde	1.84%
Ethanone, 1-(2-methylphenyl)-	2.09%	Phenol, 2-methyl-	1.61%
1H-Inden-1-one, 2,3-dihydro-	2.06%	Benzenamine, N-ethyl-3-methyl-	1.55%
Phenol, 2-methyl-	2.02%	1H-Inden-1-one, 2,3-dihydro-	1.48%
Benzenepropanenitrile	1.92%	2,3'-Dipyridyl	1.44%
1,3-Dicyanobenzene	1.49%	Pyridine	3.87%
Pyridine, 3-ethenyl-	1.36%	Phenol, 2-methoxy-	1.28%
2-Furancarboxaldehyde, 5-methyl-	1.26%	Pyridine, 3-methyl-	1.23%
4-Pyridinecarbonitrile	1.14%	1,3-Dicyanobenzene	1.15%
2-Cyclopenten-1-one, 2,3-dimethyl-	1.05%	Cedrol	1.15%
2-Furanmethanol	1.02%	2-Pyridinecarbonitrile	1.13%
pyridine	0.97	2(3H)-Furanone, 5-heptyldihydro-	1.09%
3-Methylpyridine	0.79	Nicotine	0.78%

temperature gradient could enhance the pyrolysis reaction, resulting in more products. Conversely, the nitrogen velocity gradient vector indicated how substances produced during pyrolysis moved within the heating pipe. A large velocity gradient could hinder heat transfer and affect the distribution and generation of pyrolysis products. Furthermore, a high velocity gradient helped quickly transport pyrolysis products to the condenser, preventing unwanted reactions with other substances in the heating pipe, which was important for the subsequent isolation and purification of specific substances from the pyrolysis oil.

Field synergy numerical calculations
The heat exchange process significantly impacts the pyrolysis of tobacco waste. Effective heat exchange enhances the efficiency of pyrolysis and accelerates the reaction. Additionally, efficient heat transfer ensures precise temperature during pyrolysis process, preventing issues like overheating or undercooling that can negatively affect the quality of the resulting products. The temperature gradient plays a crucial role in determining the pyrolysis and the type of reactions that occur. In regions of higher temperature, pyrolysis reactions are faster, potentially leading to the formation of more light hydrocarbons and gaseous products. However, uneven temperature distribution can cause variations in the quality and composition of the pyrolysis products, as different compounds break down at different temperatures. The rate of gas fluidization also influences the efficiency of heat transfer and material contact. Higher fluidization rates can improve heat transfer and promote more complete pyrolysis, but they may also result in incomplete reactions. If the fluidization rate is too high, it can carry partially reacted intermediates out of the reaction zone, compromising the quality and yield of the final products. Therefore, precise control of both the temperature gradient and gas fluidization rate within the pyrolysis pipe is essential for optimizing the process and improving product quality. Achieving this requires careful experimentation simulation to fine-tune

operating conditions for optimal results. Based on the synergistic relationship of equation (2), enhancing the fluid's heat transfer involved considering the synergy between the velocity $\bar{U}$ and the temperature gradient $\nabla\bar{T}$. A smaller synergistic angle α indicated stronger heat transfer within the fluid. Furthermore, a smaller magnitude of the velocity vector $|\bar{U}|$ resulted in lower fluid flow resistance, while a larger magnitude of the temperature gradient vector $|\nabla\bar{T}|$ enhanced heat transfer between the fluid and the wall surface. Figure 5 presented the cloud diagram of the heater field's synergistic calculation at 450°C under various nitrogen flow rates, showing that both the synergy between the velocity $\bar{U}$ and the temperature gradient $\nabla\bar{T}$ and the heat exchange were improved at lower nitrogen flow rates. The results indicated that, as the nitrogen flow rate decreased, the area where the synergy angle was less than 90° gradually expanded. Additionally, the region with a synergy angle below 90° was primarily concentrated in the middle of the heating pipe, while the area with a synergy angle of 0° appeared downstream of the heating pipe at nitrogen flow rates of 0.15 m/s and 0.25 m/s. This occurred mainly because, at lower nitrogen flow rates, the heat source on the heating pipe wall could effectively heat the gas, resulting in localized high temperature. The field synergy calculation for the heating pipe with an N_2 flow rate of 0.35 m/s at various temperatures showed that the synergy angle between the temperature gradient vector and the velocity vector demonstrated little variation with temperature (Figure 6), which was because temperature changes had a minimal minor impact on the velocity field. In fluid dynamics, the temperature gradient typically affected the velocity field. For instance, in convection, it could induce convective motion within the fluid. However, the impact of temperature changes on the velocity field might sometimes be less pronounced, likely because the density of N_2 varied only slightly with temperature, which resulted in minimal changes in the field synergy angle between the temperature gradient vector and the velocity vector as temperature changes. According to the results of this study, 450°C was
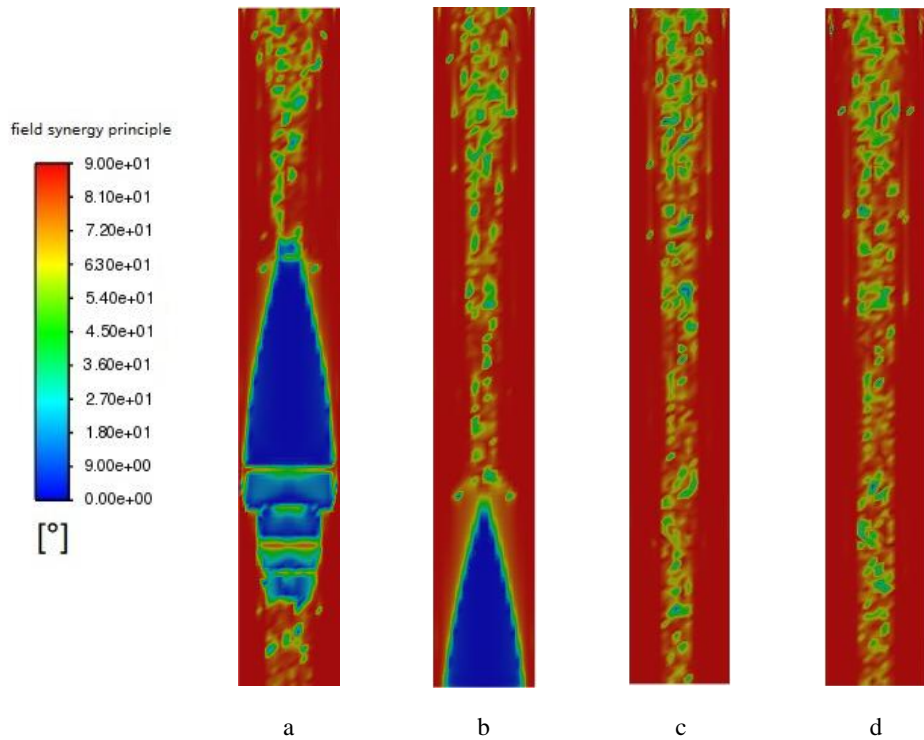
Figure 5. Calculation diagram of heating pipe field synergy principle with different N$_2$ flow rate at 450℃ (a: 0.15 m/s, b: 0.25 m/s, c: 0.35 m/s, d: 0.45 m/s).
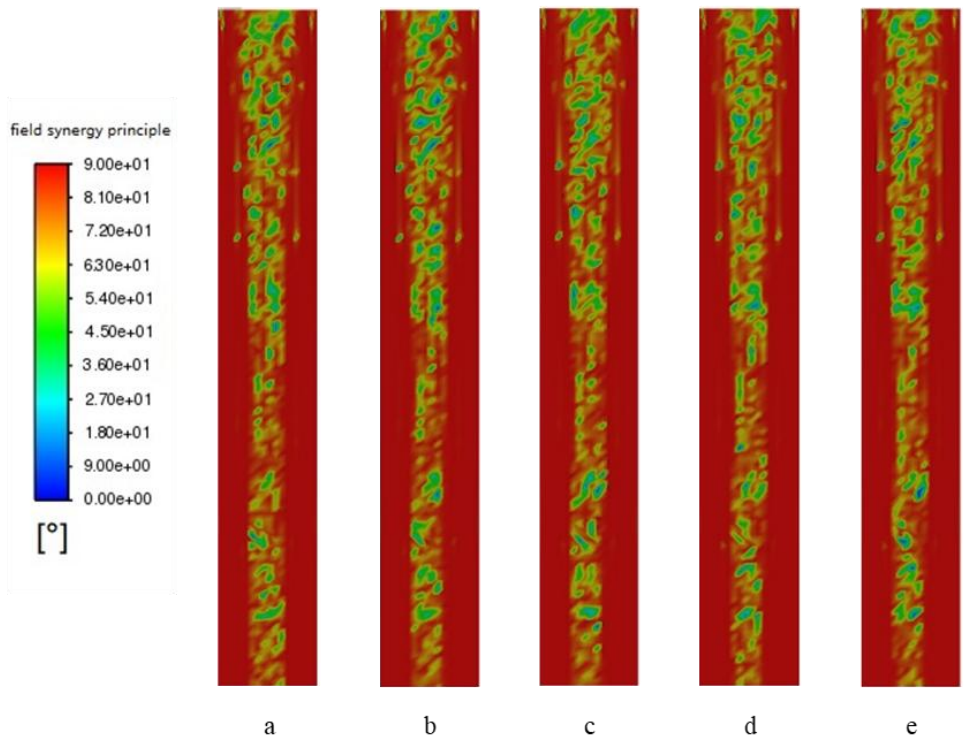

Figure 6. Calculation diagram of heating pipe field synergy principle with different temperatures at N$_2$ flow rate of 0.35m/s (a: 200℃, b: 300℃, c: 400℃, d: 500℃).

the optimal temperature for producing nicotine and aroma compounds in tobacco waste pyrolysis. When using N_2 as the fluidizing gas, increasing the temperature led to minimal changes in the synergy angle and did not significantly enhance heat transfer efficiency, while also consuming more energy, which was not ideal for energy conservation.

Conclusion

This study conducted an in-depth investigation into the pyrolysis behavior of tobacco waste through fluidized bed pyrolysis and field synergy numerical calculations with a particular focus on the release of nicotine and aromatic compounds. During the pyrolysis of tobacco waste, the amounts of nicotine and aromatic compounds varied with increasing temperature. At higher temperatures, nicotine broke down and reacted chemically, resulting in different compounds. The release of aromatic compounds was also strongly affected by temperature, leading to a wider variety. The levels of both nicotine and aromatics peaks at 450°C, indicating this temperature as optimal for their production. Numerical calculations based on field synergy principles had shown that heat transfer efficiency was crucial in the pyrolysis of tobacco waste. Lower nitrogen flow rates improved the synergy between velocity and temperature gradients in the heating pipe, leading to better heat transfer efficiency. Additionally, both temperature gradients and nitrogen flow rates significantly influenced the yield of pyrolysis oil with notable increases observed at temperatures above 450°C and nitrogen flow rates greater than 0.35 m/s. However, excessively high temperatures and gas flow rates could compromise the quality of pyrolysis oil. In fluidized beds with low gas flow rates, pyrolysis reactions were more efficient and demonstrated better heat transfer efficiency. Careful control of temperature and velocity gradients was essential for optimizing the pyrolysis process and enhancing product quality and yield. The findings of this study provided a critical theoretical and experimental basis for the utilization of tobacco waste resources, offering valuable insights for the green energy and chemical industries.

Acknowledgements

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