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GAS CHROMATOGRAPHIC ANALYSIS OF THE PYROLYSIS DISTILLATE FRACTION ISOLATED AT 200°C THROUGH A RASCHIG RING PACKING

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Abstract. A pyrolysis distillate was fractionated at 200 °C using a laboratory-scale distillation column packed with glass Raschig rings, providing stable vapor–liquid contact under atmospheric pressure. The collected fraction was subsequently characterized by gas chromatography–mass spectrometry (GC–MS) to determine its chemical composition. The analysis revealed that the fraction is predominantly composed of aromatic and polyaromatic compounds, with indene, naphthalene, azulene, and their derivatives as the main constituents. Quantitative evaluation indicated a significant contribution of C_{10} compounds, demonstrating the enrichment of medium-boiling aromatic species. The results confirm the suitability of Raschig ring packing for the controlled fractionation of pyrolysis distillates and highlight the potential of the obtained fraction for further use as a chemical feedstock or intermediate for value-added products.

Keywords: Pyrolysis distillate, raschig ring packing, fractionation, gas chromatography–mass spectrometry, hydrocarbons, C_{10} fraction

Аннотация. Пиролизный дистиллят был фракционирован при температуре 200 °C с использованием лабораторной ректификационной колонны, заполненной стеклянной насадкой в виде колец Рашига, что обеспечило стабильный контакт пар–жидкость при атмосферном давлении. Полученная фракция была охарактеризована методом газовой хроматографии–масс-спектрометрии (ГХ–МС) с целью определения ее химического состава. Результаты анализа показали, что фракция преимущественно состоит из ароматических и полиароматических соединений, основными компонентами которых являются инден, нафталин, азулен и их производные. Количественная оценка выявила значительную долю соединений состава C_{10}, что свидетельствует об обогащении фракции среднекипящими ароматическими компонентами. Полученные результаты подтверждают эффективность применения насадки колец Рашига для контролируемого фракционирования пиролизных дистиллятов и указывают на перспективность использования выделенной фракции в качестве химического сырья или промежуточного продукта для получения материалов с добавленной стоимостью.

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Ключевые слова: Пиролизный дистиллят, насадка кольца Рашига, фракционирование, газовая хроматография–масс-спектрометрия, углеводороды, фракция C_{10}.

Annotatsiya. Piroliz distillati atmosfera bosimi sharoitida bug‘–suyuqlik fazalari o‘rtasida barqaror kontaktni ta’minlovchi shisha Rashig halqalari bilan to‘ldirilgan laboratoriya miqyosidagi distillash kolonnasida 200 °C haroratda fraksiyalandi. Olingan fraksiya uning kimyoviy tarkibini aniqlash maqsadida gaz xromatografiyasi–massa spektrometriyasi (GC–MS) usuli yordamida tavsiflandi. Tahlil natijalari fraksiyaning asosan aromatik va poliaromatik birikmalardan tashkil topganligini, bunda inden, naftalin, azulen hamda ularning hosilalari asosiy komponentlar ekanligini ko‘rsatdi. Miqdoriy baholash C_{10} tarkibli birikmalarning sezilarli ulushga ega ekanligini aniqladi, bu esa o‘rta qaynash haroratiga ega aromatik moddalarning boyitilganligini tasdiqlaydi. Olingan natijalar Rashig halqali nasadkaning piroliz distillatlarini boshqariladigan tarzda fraksiyalash uchun samarali ekanligini hamda ajratib olingan fraksiyaning kimyoviy xomashyo yoki yuqori qo‘shilgan qiymatga ega mahsulotlar ishlab chiqarish uchun oraliq mahsulot sifatida qo‘llash istiqbollarini ko‘rsatadi.

Kalit so‘zlar: piroliz distillati, Rashig halqali nasadka, fraksiyalash, gaz xromatografiyasi–massa spektrometriyasi, uglevodorodlar, C_{10} fraksiya.

INTRODUCTION.

Pyrolysis distillates represent a complex mixture of hydrocarbons formed during the thermal decomposition of polymeric and heavy hydrocarbon feedstocks [1]. Due to their wide boiling range and heterogeneous composition, effective fractionation and detailed compositional analysis of pyrolysis-derived products are essential for their rational utilization as fuels, chemical feedstocks, or functional additives [2]. In this context, distillation-based separation combined with advanced analytical techniques plays a key role in understanding the chemical nature of individual fractions [3].

Packed columns equipped with Raschig ring packing are widely applied in laboratory-scale fractionation due to their simple design, chemical inertness, and ability to provide efficient vapor–liquid contact with relatively low pressure drop [4]. The use of glass Raschig rings is particularly advantageous when separating thermally sensitive pyrolysis products, as they minimize secondary reactions and contamination while ensuring stable separation conditions. Fractionation at controlled temperatures allows the isolation of narrow boiling fractions suitable for subsequent analytical characterization [5].

Gas chromatography (GC) is one of the most powerful and reliable methods for analyzing complex hydrocarbon mixtures, enabling the identification and semi-quantitative determination of individual components within distillate fractions [6].

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GC analysis provides valuable insight into the distribution of paraffinic, olefinic, naphthenic, and aromatic hydrocarbons, which directly influences the physicochemical properties and potential applications of the obtained fractions [7-8].

In the present study, a pyrolysis distillate was fractionated at 200 °C using a laboratory column packed with glass Raschig rings, and the isolated fraction was subjected to gas chromatographic analysis. The aim of this work is to characterize the chemical composition of the 200 °C fraction and to evaluate the effectiveness of Raschig ring packing for the controlled separation of pyrolysis distillates under laboratory conditions [9].

MATERIAL AND METHODS.

Materials

The pyrolysis distillate used in this study was obtained from the thermal decomposition of hydrocarbon-based feedstock under controlled pyrolysis conditions. Prior to fractionation, the distillate was filtered to remove suspended solid impurities and stored in sealed glass containers to prevent evaporation and oxidative degradation.

Glass Raschig rings were employed as the column packing material. The rings were chemically inert, cylindrical in shape, and characterized by a height-to-diameter ratio of approximately 1:1, ensuring effective vapor–liquid contact during the fractionation process.

Analytical-grade carrier gases and calibration standards were used for gas chromatographic analysis. All reagents and solvents applied in the analytical procedures were of chromatographic or analytical purity.

Fractionation Procedure

Fractionation of the pyrolysis distillate was carried out using a laboratory-scale distillation column packed with glass Raschig rings. The packed section provided an extended contact surface between the rising vapors and descending condensate, enabling efficient separation of the distillate components.

The distillation process was conducted under atmospheric pressure. The distillate was gradually heated, and the fraction corresponding to a vapor temperature of 200 °C was collected after thermal stabilization of the system. The collected fraction was allowed to cool to ambient temperature and subsequently stored in airtight glass vials prior to chromatographic analysis.

GC-MS Analysis

Mass chromatographic analysis of the 200 °C fraction was performed using a gas chromatograph equipped with a flame ionization detector (FID). Separation was achieved on a capillary column suitable for hydrocarbon analysis.

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The carrier gas was supplied at a constant flow rate, and the injector was operated in split mode. The oven temperature program was optimized to ensure effective separation of light and medium hydrocarbon components. Detector and injector temperatures were maintained at levels sufficient to prevent condensation of high-boiling compounds.

Chromatograms were processed using dedicated chromatographic software. Individual components were identified based on their retention times by comparison with reference standards and literature data. Semi-quantitative analysis was performed using peak area normalization.

RESULT AND DISCUSSION.

To evaluate the chemical composition of the fraction obtained at 200 °C by fractionation of the pyrolysis distillate using a column packed with Raschig rings, gas chromatography–mass spectrometry (GC–MS) analysis was performed. The analysis enabled the identification of individual hydrocarbon components and provided insight into the distribution of compound classes present in the selected fraction. The obtained GC–MS results are presented in Figure 1, illustrating the chromatographic profile and corresponding mass spectral information of the 200 °C fraction.

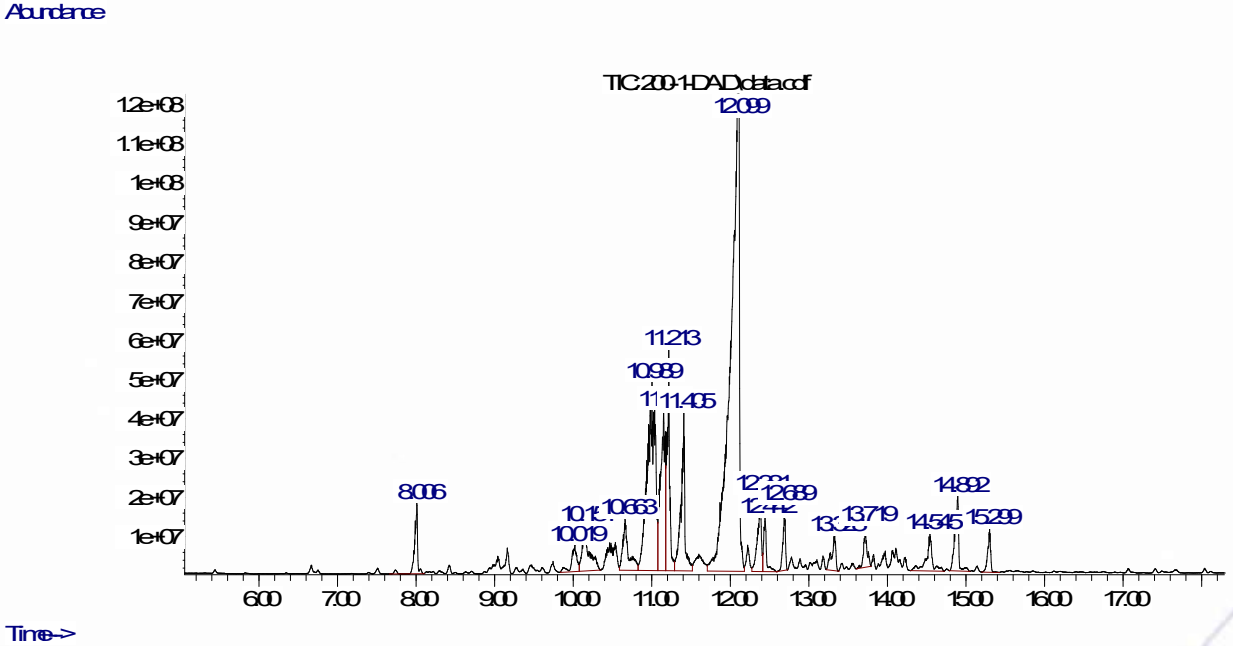


Figure 1. GC–MS chromatogram of the pyrolysis distillate fraction obtained at 200 °C using a Raschig ring packed column.

Table 1.

GC–MS analysis of the pyrolysis distillate fraction obtained at 190 °C

No.	Retention time, min	Content, %	Compound	Molecular formula
1	8.006	2.01	Benzene	C_6H_6

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2	10.019	1.39	Benzonitrile	C_7H_5N
3	10.151	3.07	4-Methylbenzonitrile	C_8H_7N
4	10.663	2.84	1H-Indene	C_9H_8
5	10.989	14.75	3,4-Dihydro-1(2H)-naphthalenone	$C_{10}H_{10}O$
6	11.151	7.24	1H-Indene	C_9H_8
7	11.213	5.79	1H-Indene	C_9H_8
8	11.405	5.87	1,8-Naphthosultone	$C_{10}H_6O_3S$
9	12.099	42.44	Isopropenylbenzene	C_9H_{10}
10	12.381	2.67	3-Pyridinecarbonitrile	$C_6H_4N_2$
11	12.442	1.54	2-Phenylpropenal	C_9H_8O
12	12.689	1.51	1-Methyl-2,3-dihydroindene	$C_{10}H_{12}$
13	13.328	1.44	1-Butynylbenzene	$C_{10}H_8$
14	13.719	1.31	2-Phenylpropenal	C_9H_8O
15	14.545	2.11	1,4-Dihydro-1,4-epoxynaphthalene	$C_{10}H_8O$
16	14.892	2.85	Allylbenzene	C_9H_{10}
17	15.299	1.19	2-Methyl-1-propenylbenzene	$C_{10}H_{12}$

GC–MS analysis of the fraction obtained at 200 °C using a Raschig ring packed column revealed a complex mixture dominated by aromatic and polyaromatic compounds. The identified components mainly include indene, naphthalene, azulene, and their oxygen- and nitrogen-containing derivatives, indicating the prevalence of medium-boiling aromatic species in the fraction. The presence of substituted aromatics and heteroatom-containing compounds reflects the typical chemical transformation pathways occurring during pyrolysis and confirms the effectiveness of the Raschig ring packing in achieving controlled fractionation under laboratory conditions.

From the identified compounds, the C_{10} fractions were separated for quantitative evaluation, and the calculated results are presented in Table 2.

Table 2.

C_{10} compounds identified in the 200 °C pyrolysis distillate fraction (GC–MS analysis)

No.	Compound	Molecular formula	Content, %
1	3,4-Dihydro-1(2H)-naphthalenone	$C_{10}H_{10}O$	0.31
2	1-Methyl-2,3-dihydroindene	$C_{10}H_{12}$	1.54
3	1,4-Dihydro-1,4-epoxynaphthalene	$C_{10}H_8O$	0.43
4	2-Methyl-1-propenylbenzene	$C_{10}H_{12}$	1.41

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5	1-Methylindene	$C_{10}H_{10}$	0.81
6	1-Methylindene	$C_{10}H_{10}$	0.31
7	Butenylbenzene	$C_{10}H_{12}$	1.90
8	1-Methylindene	$C_{10}H_{10}$	1.16
9	Alkylated indene (C_{10} isomer)	$C_{10}H_{10}$	2.85
10	1-Naphthalenol	$C_{10}H_8O$	13.91
11	Azulene	$C_{10}H_8$	5.68
12	Naphthalene	$C_{10}H_8$	4.00
13	1,4-Naphthalenedione	$C_{10}H_6O_2$	0.24
14	Halogenated naphthalene	$C_{10}H_7X$	0.32
15	1-Methylindan-2-one	$C_{10}H_{10}O$	0.46
16	Azidonaphthalene	$C_{10}H_7N_3$	0.28

According to the data presented in Table 2, the total content of C_{10} compounds in the fraction obtained at 200 °C using a Raschig ring packed column reaches 46.41%, indicating that this fraction is predominantly enriched with medium-boiling aromatic components.

The C_{10} fraction is mainly composed of naphthalene and its derivatives, including 1-naphthalenol (13.91%), naphthalene (4.00%), azulene (5.68%), and 1,4-naphthalenedione (0.24%), which together confirm the dominance of condensed aromatic structures. In addition, indene and alkyl-substituted indene derivatives (approximately 8.5% in total) were detected, suggesting that cyclization and re-aromatization reactions actively occurred during the pyrolysis process.

The presence of oxygen- and nitrogen-containing C_{10} compounds, such as naphthalenol, naphthalene dione, and azonaphthalene, reflects the complex chemical nature of the pyrolysis distillate and indicates that the fractionation was carried out under relatively mild conditions, limiting excessive thermal degradation. Overall, the obtained results demonstrate that the use of Raschig ring packing enables effective separation and concentration of C_{10} aromatic fractions from pyrolysis distillates under laboratory conditions.

CONCLUSION.

In this study, a pyrolysis distillate was successfully fractionated using a laboratory column packed with Raschig rings, and the fraction collected at 200 °C was systematically characterized by GC–MS analysis. The results demonstrated that the selected fraction is dominated by aromatic and polyaromatic compounds, confirming the effectiveness of the applied packing in providing stable vapor–liquid contact and controlled separation.

Quantitative evaluation revealed that C_{10} compounds constitute 46.41% of the 200 °C fraction, with naphthalene, azulene, indene, and their derivatives being

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the major components. The presence of oxygen- and nitrogen-containing C_{10} species further reflects the complex chemical nature of pyrolysis products and indicates that fractionation was achieved without excessive secondary thermal degradation.

Overall, the findings confirm that Raschig ring packed columns are suitable for the selective isolation of medium-boiling aromatic fractions from pyrolysis distillates under laboratory conditions. The obtained C_{10}-rich fraction shows potential for further utilization as a chemical feedstock, solvent component, or intermediate for value-added products, supporting the rational upgrading of pyrolysis-derived materials.

REFERENCES

1. Wang B., Song Y.-B., Wang F., Fan Y.-C., Cheng N., Duan P.-G. Comparative study on properties of waste tyre pyrolysis oil and its distillates obtained by molecular distillation. *Journal of Analytical and Applied Pyrolysis,* 2025, 188, 107046.
2. Zhang X., Xie Y., Wang H., Wang L., Tao G., Ji H. Influence of distillates (petroleum) on microcrystalline cellulose pyrolysis. *Journal of Analytical and Applied Pyrolysis,* 2023, 170, 105878.
3. Zhan, Y., Ji G., Ullah F., Li A. Polyoxometalate catalyzed oxidative desulfurization of diesel range distillates from waste tire pyrolysis oil. *Journal of Cleaner Production,* 2023, 389, 136038.
4. Barbero-López A., Chibily S., Tomppo L., Salami A., Ancin-Murguzur F. J., Venäläinen M., Lappalainen R., Haapala A. Pyrolysis distillates from tree bark and fibre hemp inhibit the growth of wood-decaying fungi. *Industrial Crops and Products,* 2019, 129, 604–610.
5. Wang F., Tian Y., Zhang C.-C., Xu Y.-P., Duan P.-G. Hydrotreatment of bio-oil distillates produced from pyrolysis and hydrothermal liquefaction of duckweed: A comparison study. *Science of The Total Environment,* 2018, 636, 953–962.
6. Brueckner T. M., Hawboldt K. A., Pickup P. G. Electrolysis of pyrolysis oil distillates and permeates in a multi-anode proton exchange membrane cell. *Applied Catalysis B: Environmental,* 2019, 256, 117892.
7. Olarte M. V., Padmaperuma A. B., Ferrell J. R., Christensen E. D., Hallen R. T., Lucke R. B., Burton S. D., Lemmon T. L., Swita M. S., Fioroni G., Elliott D. C., Drennan C. Characterization of upgraded fast pyrolysis oak oil distillate fractions from sulfided and non-sulfided catalytic hydrotreating. *Fuel,* 2017, 202, 620–630.
8. Suleman F., Muhbat S., Uddin F., Hashmi S., Borhan A., Ahmad F., Ahmad N. Influence of co-pyrolysis temperature on the characteristics of diesel-like fuel produced from waste frying and engine oils. *Journal of Analytical and Applied Pyrolysis,* 2025, 193(Part 1), 107352.

ISSN 3030-3907

9. Dammann M., Hüsing F., Santo U., Böning D., Mancini M., Kolb T. Characterisation of beech wood pyrolysis oil: Chemical and physical properties and decomposition kinetics. *Fuel,* 2025, 404(Part A), 134897.

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