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Patent Analysis, Technological Gaps and Development Prospects of Combined Ultrasonic and Laser Exhaust Gas Cleaning

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Abstract. *A literature and patents on gas purification using ultrasound and laser radiation is presented. It confirms that ultrasound is effective for fine particle coagulation, while laser radiation works well for oxidizing and dissociating harmful compounds. Although many patents exist for each method separately, none combine them in a single system, particularly in muffler design. Patent analysis shows technological stagnation, with 53.3% of patents over 20 years old and few recent developments. The findings support the feasibility of a combined approach using ultrasound and laser either synergistically or sequentially which could lead to innovative mufflers enabling multi-stage purification without catalytic converters or full exhaust system replacement.*

Keywords: *motor vehicles, internal combustion engine, exhaust gas cleaning system, ultrasonic coagulation, laser treatment.*

Introduction

Vehicle exhaust pollution is rising with the growing fleet, increasing PM, NOx, hydrocarbons, and CO_2 that harm health and warm the climate. "Euro" standards mandate catalytic converters, but these are costly, clog, work poorly when cold, and have limited lifetimes – so they're often removed or replaced with ineffective parts.

An alternative is a combined ultrasonic + laser approach: ultrasound agglomerates fine particles; laser radiation oxidizes/dissociates toxic compounds. This could deliver multi-stage cleanup – from particulates to organic/carcinogenic species – inside the muffler.

Hypothesis: simultaneous or sequential ultrasound and laser exposure in a muffler will markedly improve exhaust purification.

The aim of study: justify the feasibility of this combined method via a literature and patent review.

The tasks of study:

- review 30+ years of papers and patents on ultrasonic and laser gas cleaning;
- quantify patent landscape (search depth, average age, country/year distribution, obsolescence);
- identify trends and technological gaps;
- formulate a scientific-technical rationale for this new niche.

The novelty of study: first to define this research direction based on a comprehensive literature/patent synthesis leveraging US–laser synergy.

The practical significance of study: basis for a new muffler design without catalytic converters/precious metals, suitable for retrofitting older vehicles and special machinery to cut emissions without replacing the entire exhaust system.

Materials and methods

To substantiate and implement the concept of combined exhaust gas purification using ultrasonic and laser radiation, an analysis of patents and international publications was conducted. The reviewed technologies include ultrasonic coagulation, self-cleaning filters, laser ablation, and high-precision particle spectroscopy.

The paper "Raising the Efficiency of Coag-

ulation of Dispersed Particles by the Action of Ultrasonic Vibrations on Gas-Dispersed Flows in Inertial Dust Collectors" shows that ultrasonic vibrations increase the probability of particle collisions, promoting their agglomeration.

The study "Comparing cleaning effects of gas and vapor bubbles in ultrasonic fields" confirms that ultrasound enlarges fine particles, facilitating their subsequent removal, and can be used for preliminary pollutant coagulation.

The article "Combination of pulsed laser ablation and inert gas condensation for the synthesis of nanostructured nanocrystalline, amorphous and composite materials" describes laser ablation, in which particles evaporate or decompose and are then removed via filtration.

The works "Multi-element analysis of airborne particulate matter collected on PTFE-membrane filters by laser ablation inductively coupled plasma mass spectrometry" and "Elemental analysis of airborne particulate matter using an electrical low-pressure impactor and laser ablation/inductively coupled plasma mass spectrometry" demonstrate that laser ablation combined with mass spectrometry enables precise determination of pollutant particle composition, which is important for environmental monitoring and the development of purification systems.

The results of the patent analysis, covering a period of 30-40 years, are presented in Table 1.

Patent JP5971355B2 (Japan) describes an ultrasonic cleaning system designed to improve the cleaning of pipes and ducts by optimally distributing ultrasonic vibrations. It ensures stable, uniform transmission of ultrasound inside long or curved pipes through strategically placed transducers and the use of

Table 1 – Patent inventions related to the research topic, covering a period of 30–40 years

№	Patent number	Year	Description of the invention
1	US3395904A	1968	One of the first patents for a laser cleaning system for aerosols – a pioneering approach in the field of laser ablation of pollutants in gas media.
2	SU1627592A1	1989	Soviet system for ultrasonic cleaning of flue gases in channels – uses ultrasonic vibrations for coagulation and deposition of solid particles [1].
3	EP0572211B1	1993	A device for cleaning liquids and gases using ultrasound in a reactor chamber. Ultrasonic waves coagulate contaminant particles, facilitating their deposition [2].
4	DE19916311A1	1999	Device for ultrasonic particle deposition inside a filter tube – uses acoustic waves for combined filter cleaning.
5	RU2159480C1	2000	Russian ultrasonic intensifier for gas cleaning in wet scrubbers – combines cavitation effects with chemical reactions.
6	US20020134770A1	2002	Method of laser ablation of contaminants and deposits from surfaces. Based on the evaporation of material under a powerful laser pulse [1].
7	US6779365B1	2004	Laser-photocatalytic reactor for decomposing harmful gas components – the laser activates photocatalysis, effectively destroying volatile organic compounds [2].
8	US6693255B2	2004	Laser system for surface cleaning and treatment. Uses an ultrashort laser pulse to remove contaminants and oxides without damaging the substrate [3].
9	CN202994225U	2012	Compact ultrasonic cleaning device for flowmeters. Effectively removes contaminants that affect measurement accuracy [4].
10	JP2013247186A	2013	Japanese device using ultrasound in combination with fluid flow to remove particles from microchannels and tubes [5].
11	CN104056817A	2014	Filtering device with self-cleaning function using ultrasound and air purging. Prevents clogging of filters in ventilation systems [6].
12	RU2447926C2	2012	Device for particle coagulation in gases using ultrasound. Particles cluster and settle in a chamber under gravity [7].
13	US10704540B2	2020	Gas compressor using laser-induced evaporation of metal foil to create a shock wave that compresses and accelerates the gas [8].
14	US20210048325A1	2021	Ultrasonic flowmeter with self-diagnostics and partial cleaning of the measuring area [9].
15	EP3999267A1	2022	Ultrasonic atomization system for powder metallurgy. Ultrasonic breakdown of agglomerates improves gas and mixture quality [10].

liquid, enhancing internal surface cleaning efficiency (Figure 1).

The system works as follows: liquid enters through the inlet (16–17) and flows along the pipe (20). An ultrasonic transducer (18a) on a probe (18) generates high-frequency vibrations, transmitted via the liquid to the pipe's inner surface (20a). These vibrations create cavitation and micro-bubble explosions, effectively removing contaminants. The used liquid is then discharged through the outlet (23).

Patent CN104056817A represents a simple and efficient automated air filter cleaning system that combines two types of action: ultrasound and air purging – allowing the filter to be kept clean without disassembly or manual labor (Figure 2).

Air enters through the filter (1), where particles are trapped. When activated via the switch (8) from the power source (9), the ultrasonic transducer (7) generates high-frequency vibrations, causing the filter walls to micro-vibrate and loosen dust. The valve (2) opens, letting compressed air from source (3) through channel (4) into the filter, blowing detached particles toward the outlet (5) for collection.

Patent US10704540B2 describes a system and method for gas compression using ultrashort laser pulses. The laser generates shock waves in the medium, allowing gas compression without the use of rotating machinery. This technology can be applied to gas purification by decomposing pollutants under the influence of shock waves (Figure 3).

In Figure 3, ultrashort laser pulses (7) pass through the optical window (29) and hit the absorber (28), causing evaporation, plasma formation, and a shock wave that compresses the gas (38) in the first chamber (5), cooled by the radiator (33). The wave is amplified in the conical second chamber (4) by wall geometry (25), then passes through a Laval nozzle (2) and exits as a compressed gas flow (8).

Patent RU2447926C2 refers to a device designed for cleaning a gas stream from dust and solid particles using ultrasonic exposure, which induces coagulation (clumping) of fine particles into larger ones that settle under the influence of gravity.

Gas with dust or smoke enters through the inlet pipe (7) into the coagulation chamber (6). The electronic generator (4) drives the piezoelectric element (3), which produces ultrasonic vibrations. These are amplified by the horn emitter (2) and spread evenly in the chamber, causing dust particles to coagulate and settle into the dust container (5).

Patents such as JP5971355B2 (efficient ultrasonic transmission in tubular channels), CN104056817A (ultrasound with air purging for automated cleaning), US10704540B2 (shock waves from ultrashort laser pulses to break down harmful components), and RU2447926C2 (ultrasonic coagulation of fine particles) together form the basis for next-generation mufflers where ultrasound and laser act jointly or sequentially to effectively neutralize pollutants in a compact exhaust system.

Results

Based on the reviewed patents, an analysis was conducted by year and country to identify peak patent activity in the field of laser and ultrasonic gas purification.

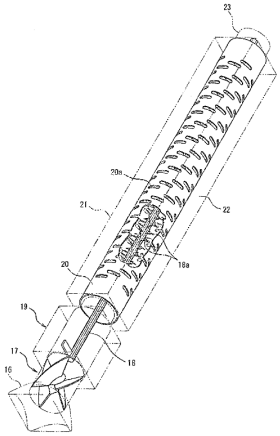

Figure 1 – Ultrasonic pipe cleaning system

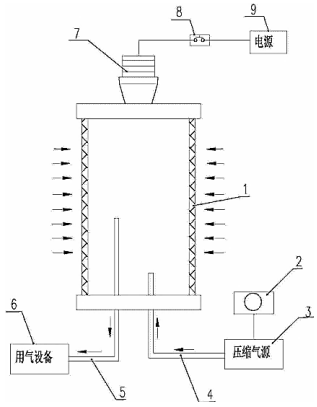

Figure 2 – Air filter cleaning system

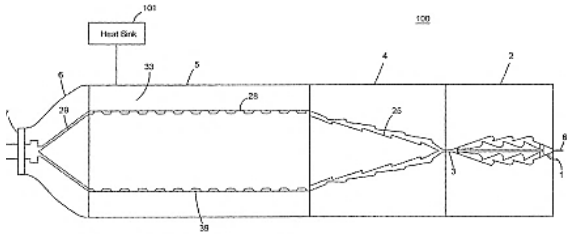

Figure 3 – Gas compression system using ultrashort laser pulses

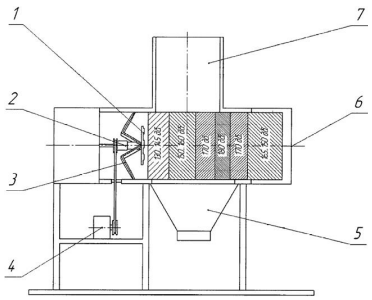

Figure 4 – Device designed to clean the gas flow from dust and solid particles

Patent activity in ultrasonic and laser gas purification peaked between 1999 and 2008, reflecting high research and engineering interest. After 2010, filings declined, likely due to reduced focus on traditional methods or a shift to proprietary, non-patented corporate developments. Geographically, the U.S. contributed early laser innovations, Russia maintained steady ultrasonic research, while Japan and Germany produced a few but advanced inventions. China's activity grew after 2010, driven by automation and self-cleaning technologies. Notably, no patents were found combining both laser and ultrasound in a single system, especially in mufflers, highlighting an unoccupied niche with strong novelty and innovation potential. The analysis also determined the depth of study, average patent age, and the share of patents over 20 years old.

Depth of the patent study:

$$D = Y_{current} - Y_{\min} = 2025 - 1968 = 57\ year,$$

where D – depth of the study;

$Y_{current}$ – current year;

$Y_{\min}$ – year of the earliest patent.

Average age of patents:

$$\overline{A} = \frac{1}{n}\sum_{i=1}^{n}(Y_{current} - Y_i) = \frac{(2025-1968)+}{15}$$

$$\frac{+(2025-1989)+...+(2025-2022)}{15} =$$

$$= 20,1\ year,$$

where Y_i – the patent number is in order

Share of patents older than 20 years:

$$P_{20+} = \left(\frac{n_{20+}}{n}\right) \times 100\% = \frac{8}{15} \times 100\% = 53,3\%,$$

where n_{20} – the patents older than 20 years;

n – total number of patents.

Patent analysis shows a study depth of 57 years, reflecting long-term interest in laser and ultrasonic gas purification separately. Yet, no patents were found combining both methods in a muffler, confirming the novelty of this approach. The average patent age is about 20 years, with most from the 1990s–2000s and few after 2020, indicating stagnation and a lack of modern applied solutions. Over half of the patents (53.3%) are more than 20 years old, underscoring the absence of recent experimental developments, especially for muffler-based exhaust gas neutralization systems.

Conclusion

The analysis of literature and patent sources confirmed the high relevance of the chosen research topic while simultaneously revealing significant gaps in current scientific and technical developments. In particular, there are currently no experimental or theoretical studies that examine the combined use of ultrasonic and laser radiation within the design of a muffler.

Moreover, the potential interaction zones between the two types of radiation – ultra-

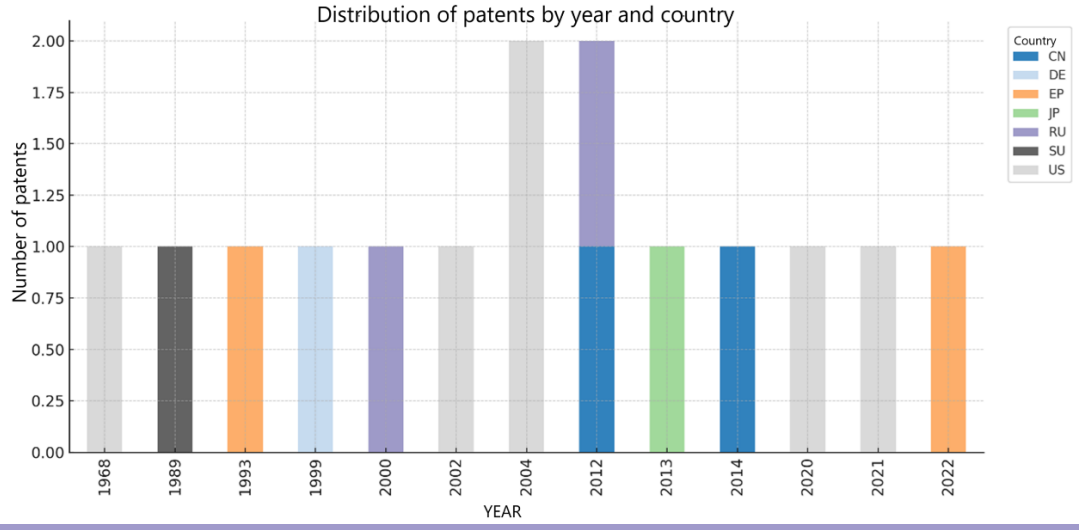

Figure 5 – Analysis of patents by year and country

sound and laser – have not been established. It remains unknown whether they act independently of each other or exert a synergistic effect on the purification processes. The optimal sequence of ultrasonic and laser exposure also remains unexplored: whether simultaneous, sequential, or pulsed activation of the emitters could enhance efficiency is yet to be determined. Furthermore, there is no physical model in the scientific literature that describes the processes of particle coagulation, dissociation, and deposition under the influence of combined radiation within the confined environment of a muffler. Regression models that could quantitatively link the parameters of ultrasonic and laser exposure to the achieved level of exhaust gas purification have also not been developed.

All of this highlights the need for a comprehensive study in this direction, underscoring the scientific novelty and potential uniqueness of the proposed research topic.

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Патенттік талдау, технологиялық олқылықтар және пайдаланылған газдарды ультрадыбыстық және лазерлік біріктірілген тазалаудың даму перспективалары

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Аңдатпа. *Ультрадыбыстық және лазерлік сәулелендуді қолданатын газдарды тазарту құрылғыларына қатысты әдебиет пен патенттік талдау нәтижелері ұсынылған. Ультрадыбыстың ұсақ дисперсті бөлшектерді коагуляциялау үшін, ал лазерлік сәулеленудің зиянды қосылыстарды тотығу мен диссоциациялау үшін тиімді екені анықталды. Жекелеген технологияларға арналған көптеген патенттердің болғанына қарамастан, олардың бір құрылғыда, әсіресе, бәсеңдеткіш құрылымында бірлесіп қолданылуын жүзеге асыратын әзірлемелер жоқ. Жүргізілген патенттік талдау соңғы жылдары технологиялық тоқырау мен қолданбалы шешімдердің болмауын көрсетеді. Патенттердің 53,3%-ы 20 жылдан асқандығы анықталды. Алынған нәтижелер негізінде ультрадыбыстық және лазерлік әсерді синергиялық немесе кезектесе қолдануға негізделген пайдаланылған газдарды біріктіріл-*

ген тазарту бағытында зерттеулер жүргізудің өзектілігі дәлелденді. Мұндай тұжырымдама жаңа ғылыми-техникалық бағытты ашады және каталитикалық бейтараптандырғыштарды қолданбай, сондай-ақ бүкіл шығару жүйесін толық ауыстырмай-ақ, газдарды көпсатылы тазартуды қамтамасыз ететін инновациялық бәсеңдеткіштерді әзірлеуге мүмкіндік береді.

Кілт сөздер: *автокөлік, іштен жану қозғалтқышы, пайдаланылған газдарды тазарту жүйесі, ультрадыбыстық коагуляция, лазерлік өңдеу.*

Патентный анализ, технологические пробелы и перспективы развития комбинированной ультразвуковой и лазерной очистки выхлопных газов

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Аннотация. *Представлен литературно-патентный анализ устройств очистки газов с использованием ультразвукового и лазерного излучения. Установлено, что ультразвук эффективен для коагуляции мелкодисперсных частиц, а лазерное излучение – для окисления и диссоциации вредных соединений. Несмотря на наличие многочисленных патентов по отдельным технологиям, отсутствуют разработки, реализующие их совместное применение в одной установке, особенно в конструкции глушителя. Проведённый патентный анализ указывает на технологический застой и отсутствие прикладных решений в последние годы. Выявлено, что 53,3% патентов старше 20 лет. На основе полученных результатов обоснована перспективность проведения комбинированной очистки выхлопных газов, предполагающая синергетическое или поочередное воздействие ультразвука и лазера. Такая концепция открывает новое научно-техническое направление и может быть использована для разработки инновационных глушителей, обеспечивающих многоступенчатую очистку газов без использования каталитических нейтрализаторов и без необходимости полной замены выхлопной системы.*

Ключевые слова: *автотранспорт, двигатель внутреннего сгорания, система очистки выхлопных газов, ультразвуковая коагуляция, лазерная обработка.*

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