

Air Pollution Sources, Emission Characteristics, and Control Technologies: A Mechanical Engineering Perspective

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Abstract

Air pollution is one of the major and serious concerns for environmental health, which occurs mainly due to industrialization, urbanization, and due to increment in automobile and fossil fuel dependency. It was realized that different systems pertaining to mechanical engineering in terms of thermal power plants, HVAC systems, and automobile exhaust are the prime contributors to air pollution and degradation. The objective of the present research work is to review various sources of air pollution, characteristics of emissions, the mechanism of generation of pollutants, pollution control, and monitoring techniques from a mechanical engineering point of view. Various types of pollutants, such as carbon monoxide, carbon dioxide, nitrogen and sulphur oxides, volatile organic matter, and particulate matter, were identified, and harmful effects are discussed. The effect of combustion characteristics, thermodynamic processes, effect of fuel ratio were discussed on the formation of pollutants. Conventional and advanced pollution control technologies were also discussed in detail. Thus, the present review systematically presents proper aspects of air pollution mitigation methods with mechanical engineering applications.

Keywords: Air Pollution, Mechanical Engineering, Emission Control, Combustion, Pollutant Monitoring.

1. Introduction

Advancements in science and technology and rapid growth in industrialization have provided many solutions to mankind in terms of excellent mobility facilities, infrastructure development, advancement in communication, etc. Besides this, it has also generated some detrimental effects in terms of various types of pollution in terms of air, water, soil, and noise pollution due to the adverse effects of industrialization. Air pollution is one of the major forms of pollution that came into existence due to the generation of poisonous gases, smoke, and dust particles that bring ecosystems to a very degraded stage [1]. It was seen that cutting of trees in the name of infrastructure development, urbanization, increased number of vehicles, increased transportation, and manufacturing facilities have majorly contributed to air pollution [2]. It was gathered from the report of the WHO that annually many lives are lost due to air pollution [3]. Again, in this context of air pollution, various pollutants namely such as particulate matter, such as PM_{2.5} and PM₁₀ particles, oxides of Sulphur and nitrogen, carbon monoxide, carbon dioxide, and ozone, were found to be the major pollutants for air pollution, which are responsible for the generation of respiratory diseases, neurological disorders, heart-related problems and even cancer [4]. It was also found that ecosystem also gets degraded due to the ill effects of air pollution in terms of acid rain, losses to agricultural activities, change in climatic conditions, poor visibility problems, and so on [5].

Air pollution is generated by the interaction of many systems related to mechanical engineering, industrial systems, and transportation systems, which involve the burning of fuels in engines, thermal and energy generation processes that involve fluid flow, and thermally driven processes [6]. Coal and gas-fired thermal power plants, incinerator, boilers of

industries, automobiles related to mobility, compressors, refrigeration, and air conditioning systems are the major sources of air pollution due to thermal-mechanical systems [7].

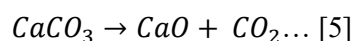
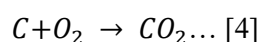
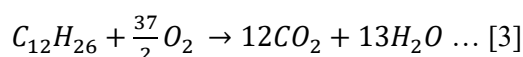
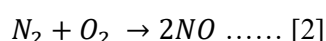
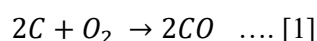
Burning and combustion of fossil fuels such as petrol, diesel, wood, coal, etc., brings air pollution significantly to the ecosystem. Incomplete and improper combustion due to certain prime reasons, such as improper mixing of air-fuel, impurities in fuel, and inefficient thermodynamic reactions at elevated temperatures, were the prime generators of air pollutants [8]. In this context, various process and operating parameters such as proper design of combustion chamber, air-fuel ratio, intensity of turbulence, and other characteristics of heat transfer processes significantly affect the behavior of emissions [9].

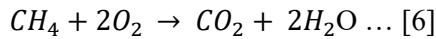
To combat the various problems of emissions and air pollutants, it was gathered that the introduction of various advanced and sophisticated technologies was introduced by mechanical engineers [10]. In this context, adaptation of renewable energy technologies, control systems for emissions, smart systems for monitoring purposes, and energy-efficient designs of systems, etc. [10]. Besides this, for air pollution control, prediction, and optimization, significant progress was cited in terms of computational fluid dynamics modelling and simulation. The introduction of industry 4.0 technologies, such as IoT, artificial intelligence, and machine learning, has contributed to the mitigation and prediction of air [11]. The objective of the present research work is to review the various aspects of air pollution sources, emission characteristics, pollutant formation mechanisms, monitoring technologies, control strategies, sustainable solutions, and future research directions from a mechanical engineering perspective.

2. Sources of Air Pollution

Sources of air pollution were mainly exhibited in the form of natural sources and man-made sources. Within the range of natural sources, it was gathered that different decomposition processes in biological forms, random eruptions of volcanoes, and storms made out of dust particles were the major sources of air pollution in terms of natural sources [12]. It was realized that human-induced sources of air pollution were major contributors to air pollution in urban scenarios as well as in industrial sites [12].

Transportation sector is one of the sectors which significantly contributed to air pollution in terms of urban pollution and generation of greenhouse gases [13]. It was gathered that diesel powered engines and gasoline-based engines severely emit harmful gases such as carbon monoxides, carbon dioxide, oxides of nitrogen, hydrocarbons, particulate matter [13]. Several different types of chemicals occur within the internal combustion engines which actually in turn of producing mechanical power produces various pollutants [14]. Equation [1] and eqn. [2] shows the chemical reaction for the formation of carbon monoxide and nitrogen oxides. Carbon monoxide forms due to incomplete combustion and occurs due to low rate of oxygen, improper timing of ignition, as well as due to rich fuel-air mixtures [15]. On the contrary, nitrogen oxide is produced during combustion at elevated temperatures and is mostly produced by diesel engines due to compression ratios of diesel engines, as well as due to lean fuel-air mixture [16]. In addition to this, hydrocarbons were also generated due to improper combustion, evaporation of fuel, and quenching of the wall [17]. On the other hand, particulate matter in terms of soot particles was also emitted due to incomplete oxidation of droplets of fuel as well as due to flame combustion, especially in diesel engines [18].





Within transportation, the aviation sector is another area where greenhouse gases and very fine particles are emitted by aircraft gas turbines [19]. Equation [3] shows the reaction of jet fuel combustion. Additionally, the marine environment generates air pollution from sulphur oxides, nitrogen oxides, and particulate matter emitted by marine diesel engines [20]. Additionally, it was observed that diesel locomotives emit pollutants into the urban environment [21]. Another sector that significantly contributes to air pollution is industry, due to combustion, processing at elevated temperatures, and material handling [22]. In this context, it was observed that thermal power plants, which work upon combustion, emit carbon dioxide, nitrogen oxides, heavy metals, and fly ash [23]. Eqn. [4] and Eqn. [5] chemical reactions for the formation of sulphur dioxide and carbon dioxide. It was found that fly ash contains mercury, alumina, silica, arsenic, and chromium [24]. In addition, it was gathered that industries that process metals and steel, and produce steel at various sites such as coke ovens, blast furnaces, and sintering processes, which in turn release metallic aerosols, volatile organic compounds, and sulphur compounds [25]. In addition, it was found that the cement industry emits carbon dioxide due to calcination and fuel combustion [26]. Eqn. [5] shows the chemical reaction for the decomposition of calcium carbonate into two products, namely calcium oxide and carbon dioxide, as shown in eqn. [5]. In addition, complex manufacturing processes such as welding, grinding, and laser cutting emit metallic fumes, volatile organic compounds, and other pollutants [27]. Outdoor and indoor air pollution were also found, occurring mainly due to the combustion of biomass and fuels for cooking [28]. It was also recognized that depletion of the ozone layer and the generation of greenhouse gases were observed due to emissions from HVAC refrigerants [29].

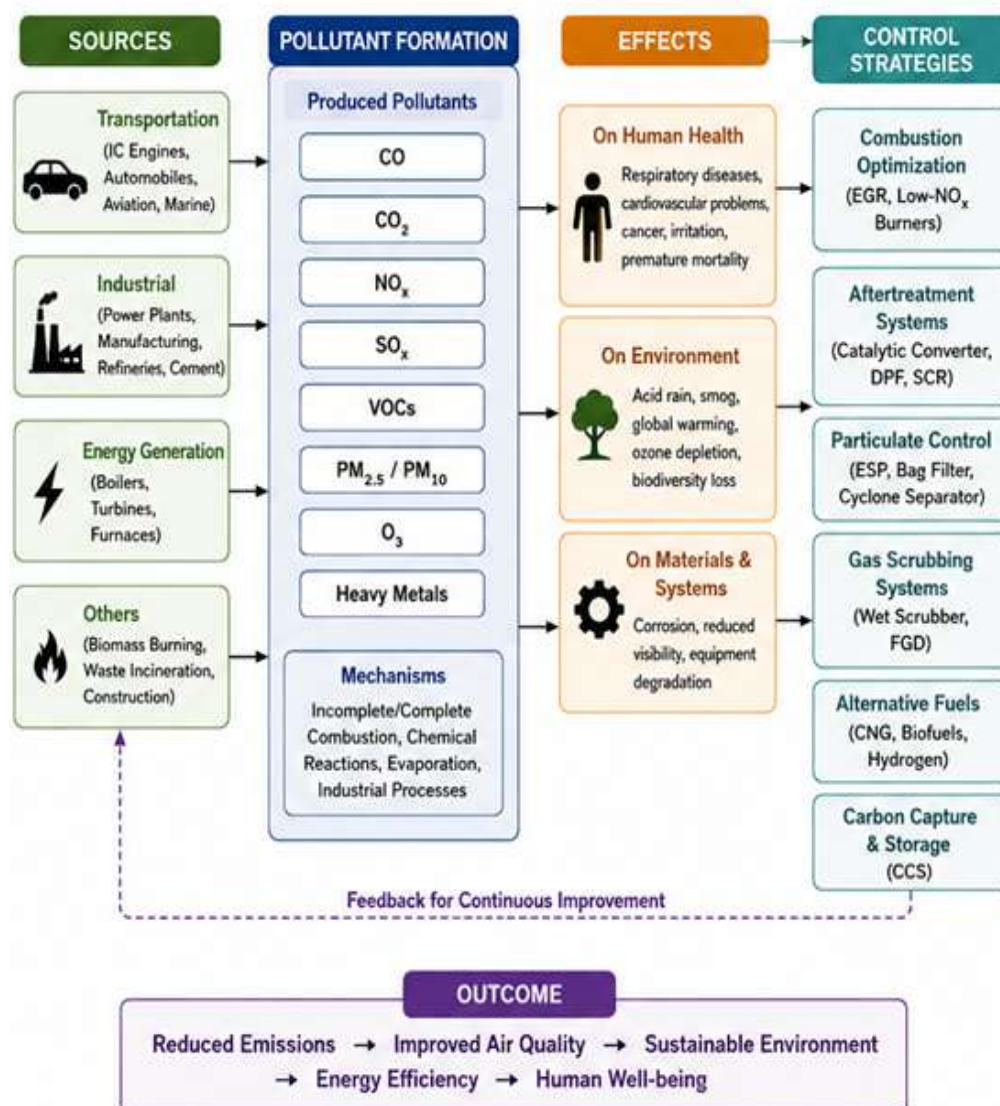


Figure 1. Sources, formation, effects: Control pathway of air pollution in mechanical engineering systems

3. Pollutants and their formation mechanisms

Carbon dioxide is one of the major pollutants in the form of a poisonous gas, which was generated due to incomplete combustion [30]. Formation of carbon monoxides increases due to the rich fuel-air mixtures at low temperature conditions [30]. In addition to this, carbon dioxide is another greenhouse gas that adds to the increase in global warming [31]. Eqn. [6] shows the chemical reaction of complete combustion in which methane, in the presence of oxygen, decomposes into carbon dioxide and water vapours [31]. Another major pollutant is nitric oxide and nitrogen oxide, and both these pollutants were responsible for the occurrence of acid rain and smog formation, also [32]. Besides this, another poisonous gas is sulphur oxides, and it was found that it was generated through coal and heavy oils [33]. Another form of pollutants, known as volatile organic compounds, was found to be generated from various types of industrial solvents, paints, and fuels due to evaporation [34]. Another category of pollutants appears in the form of fine particles, which can deeply penetrate into human blood as well as into the respiratory system [35]. Table 1 shows the major air pollutants and their effects.

Table 1. Major Air Pollutants and Their Effects

Pollutant	Major Sources	Major Effects
CO	IC engines, boilers	Toxic to humans, reduces oxygen transport
CO ₂	Fuel combustion, industries	Global warming and climate change
NO _x	Diesel engines, power plants	Acid rain and smog formation
SO _x	Coal combustion, marine fuel	Respiratory problems and acid rain
VOCs	Paints, solvents, fuels	Ozone and smog formation
PM _{2.5} / PM ₁₀	Diesel engines, industries	Lung and cardiovascular diseases

4. Mechanical Engineering aspects of air pollution generation

There are various mechanical engineering aspects that are collectively responsible for the generation of air pollution. One of the important mechanical engineering aspects of air pollution, which generate air pollution, is combustion inefficiencies, which can be visualized in terms of poor atomization of air fuel mixture, insufficient turbulence, delays in ignition, and due to incomplete combustion, severely increases the formation of pollutants [36]. Another important aspect of mechanical engineering, which is responsible for air pollution generation, is the fuel-air ratio [37]. Fuel-air ratio is defined as the proportion of fuel to air by mass present in a combustion chamber, and it was observed that richness of mixture produces carbon monoxide and hydrocarbons, whereas lean mixtures increase the tendency of formation of nitrogen oxide [37]. Another important factor in terms of mechanical engineering aspects is heat transfer and thermal efficiency, and it was gathered that poor thermal efficiency of engines results on increment in fuel consumption as well as in the rate of emissions levels [38]. Turbulence significantly influences flame propagation characteristics and plays a crucial role in maintaining combustion stability by enhancing the mixing of fuel and oxidizer within the combustion chamber [39]. Another mechanical engineering aspect responsible for air pollution generation is turbulence [39]. Turbulence directly affects the propagation of flame and aids in maintaining the stability of combustion, thereby increasing the mixing of fuel and oxidizer [39]. Another mechanical engineering aspect is mechanical wear, which decreases the lubrication layers and increases emissions of particulate matter [40].

5. Emission measurement and monitoring techniques

Gas analyzers are generally found in the form of Infrared and electrochemical analyzers, which measure CO, CO₂, HC, NO_x, and SO_x emissions [41]. In addition to these, monitoring particulate matter is typically achieved using laser-based scattering systems and gravimetric methods [42]. Furthermore, it is now common to use IoT-driven sensors, which also help in real-time monitoring of air pollution via wireless communication [43]. Another important monitoring technique is the application of computational fluid dynamics, which aids in analyzing the behavior of combustion, dispersion of

pollutants, and the behavior of thermal systems [44]. Finally, due to advancements in artificial intelligence, recent machine learning models have become capable of predicting pollutant concentrations [45].

6. Pollution Control Technologies

There are various types of devices and technologies that help in the reduction of emissions from vehicles and industrial pollution sources. It was found that in the field of automobiles, catalytic converters are utilized for reducing the levels of pollutants, namely carbon monoxide, hydrocarbons, and nitrogen oxides [46]. Besides this, it was found that exhaust gas recirculation was employed for the minimization of the formation of nitrogen oxides, thereby reducing the temperature of combustion [47].

Besides this, it was also found that soot particles coming from diesel exhaust gases can be efficiently captured through diesel particulate filters [48]. In addition to this, it was realized that in order to convert nitrogen oxides into useful nitrogen and water via injection of ammonia through selective catalytic reduction systems [49]. Besides this, in the context of industrial applications, cyclone separators help in capturing particulate matter of large size by utilizing centrifugal force [50]. Besides this, it was realized that bag filters were utilized for capturing fine particles in a highly efficient manner [51]. On the other hand, electrostatic precipitators were employed to remove particles through electrostatic attraction [52]. In addition to these, wet scrubbers help in the absorption of gaseous pollutants through spray liquid [53]. It was also found that carbon capture and storage technology was used for removing industrial emissions of carbon dioxide and thereafter storing it underground for control of greenhouse gas emissions [54]. Table 2 shows the major air pollution control techniques.

Table 2. Major Air Pollution Control Technologies

Technology	Application	Major Benefit
Catalytic Converter	Automobiles	Reduces CO, HC, and NO _x
EGR System	IC engines	Lowers NO _x emissions
DPF	Diesel engines	Removes soot particles
SCR	Heavy diesel systems	Converts NO _x to nitrogen
ESP	Thermal power plants	Removes fly ash particles
Wet Scrubber	Industrial exhaust	Removes gases and particles
Cyclone Separator	Dust collection systems	Removes large particulates
Carbon Capture System	Power plants	Reduces CO ₂ emissions

7. Conclusion

Air pollution is recognized as one of the major environmental challenges due to the intervention of increment in transportation, industrialization, thermal power plants, and manufacturing activities. It was realized that mechanical engineering systems significantly influence pollutant formation through combustion, heat transfer, thermodynamics, and fluid flow processes. The present review focussed on major pollution sources, emission characteristics, monitoring methods, and advanced control technologies from a mechanical engineering perspective. Technologies such as catalytic converters, diesel particulate filters, electrostatic precipitators, wet scrubbers, and carbon capture systems have shown considerable effectiveness in reducing emissions. Modern monitoring approaches including computational fluid dynamics and IoT-based sensing systems have improved real-time pollution analysis and prediction. However, challenges related to particulate emissions, combustion inefficiencies, and greenhouse gas reduction still remain. Future research should focus on sustainable engineering solutions, energy efficiency, and low-emission technologies.

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