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Review article

Critical review of condensable particulate matter

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ABSTRACT

Particulate matter emitted by fuel combustion has become a major air pollutant. It comes in the form of filterable particulate matter (FPM) and condensable particulate matter (CPM). In the past, people focused on FPM due to its large emission amount. Such active research prompted the rapid development of FPM control technology. At present, FPM is effectively controlled, and its emission concentration is extremely low. By contrast, the emission concentration of CPM is higher than that of FPM and requires immediate attention. Therefore, people are paying close attention to CPM. Nevertheless, CPM is still poorly understood. On the basis of existing research, this study reviews CPM, including its concept, formation mechanism, and hazards. CPM test methods and the factors that affect the accuracy of CPM measurement are also discussed. Improvement methods focusing on CPM measurement are introduced. The results of previous research on CPM characteristics are summarized. Finally, possible CPM control techniques are discussed.

1. Introduction

Fossil fuels (coal, petroleum, and natural gas) account for about 86% of the world's primary energy consumption. Particulate matter (PM) emitted by fossil fuel combustion is the main cause of air pollution such as haze [1,2]. Condensable particulate matter (CPM) is a material that is gaseous at flue gas temperature before discharge but is formed as a particulate substance after dilution and cooling in the plume. Filterable particulate matter (FPM) is another type of particulate that is commonly known as soot. Total particulate matter (TPM) is composed of CPM and FPM. With the rapid development of FPM control technology, the emission concentration of FPM is considerably decreasing [3,4], making the discharge of CPM an issue that merits attention [5]. At present, people are focusing on CPM because its characteristics make it difficult to remove. However, only a few studies have explored CPM, and relevant knowledge about CPM is limited. For this reason, we collected relevant literature and conducted a review on the status of CPM research.

Corio and Sherwell [6] found that CPM accounts for about 76% of the total PM_{10} emitted by coal-fired boilers and about 50% of the total PM_{10} emitted by oil- and natural gas-fired boilers. After testing the CPM emission of three coal-fired boilers (300–1000 MW), Pei [7] found that the average CPM concentration in exhaust gas is $21.2 \pm 3.5\ mg/m^3$ (i.e. about $25\ mg/Nm^3$), accounting for 51% of the TPM. Existing data demonstrated that the emission concentration of CPM and its proportion of emissions are very large, so CPM's potential harm to the environment cannot be ignored.

At present, no country in the world has set limits on CPM emissions. Existing regulations only focus on FPM emissions. For example, the US Environmental Protection Agency (EPA) stipulates that the emission limit of particulate matter in coal-fired power plants is $20\ mg/Nm^3$ [8]. The EU stipulates that the particulate emission limit of coal-fired power plants is $30\ mg/Nm^3$ [9]. China is a large coal-consuming country. China stipulates that the particulate emission limit for key areas is $20\ mg/Nm^3$ [10]. In the past, people's main efforts were focused on the control of FPM due to the huge amount of FPM emissions. As a result, FPM control technology rapidly developed. Nowadays, coal-fired power plants in China are implementing ultra-low-emission reform [11], which makes FPM emissions reach advanced levels below $5\ mg/Nm^3$. After the resolution of FPM emissions, people's attention began to shift to CPM. China's Ministry of Science and Technology released a key national R&D project about the "Causes and Control of Air Pollution" in 2016. This project put forward to solve the key technology of CPM control [12], which is a research direction that will be developed in the future.

The authors reviewed the research topic of CPM to help researchers gain a systematic understanding of CPM. This review provides researchers with detailed information on the concept of CPM, its characteristics, test methods, emissions, and composition. The emission concentration of CPM in coal combustion is much higher than that in other types of fuel combustion [6]. Current CPM research has mainly focused on coal-fired sources. Therefore, this critical review concentrates on coal-fired stationary sources.

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2. Basic cognition of CPM

As a result of the limited research attention to CPM in the past, there is a lack of understanding about CPM. There are also some misunderstandings in people's cognition toward CPM. Therefore, we begin with an in-depth explanation of the definition of CPM.

2.1. EPA's definition of CPM

The CPM emission issue was recognized by the EPA as early as 1983 [13]. In EPA Method 202 [14], the EPA defined CPM as "material that is vapor phase at stack conditions but which condenses and/or reacts upon cooling and dilution in the ambient air to form solid or liquid PM immediately after discharge from the stack." In the same document, CPM was defined as "a component of primary PM". CPM is gaseous matter in the flue stack. After its release, it enters the particle state (solid particle or liquid particle) immediately through condensation or reaction with other atmospheric substances. The critical point of the CPM's definition is the temperature of the flue gas outlet. The particles formed before discharge belong to FPM, and the particles formed after discharge belong to CPM.

Because CPM has two states: gaseous state before discharge and particle state after discharge, and some topics of this paper such as hazards and sizes are aimed at the CPM in particle state, we specially define the abbreviation of "CPM_P" to represent the CPM in particle state in order to avoid confusion.

In order to further clarify the definition category of CPM, a few brief discussions on the relationship between CPM and water vapor, secondary particles, volatile organic compounds (VOCs), and SO_3 have been carried out as following.

2.1.1. Water vapor and CPM

According to CPM's definition, water vapor in flue gas should fall within the scope of CPM. However, given that water vapor may condense into environmentally harmless liquid water droplets after discharge and vaporize again after a time period, EPA methods do not count water vapor in CPM when measuring the total CPM.

2.1.2. Secondary particles and CPM

People often confuse secondary particles with CPM. Actually, CPM is different from secondary particles [15]. Secondary particles are not emitted directly as CPM. On the contrary, they are formed by long-term physicochemical reactions between emission gases, such as SO_2, NO_x and atmospheric components [16,17].

2.1.3. VOCs and CPM

VOCs are a general designation of organic coal-fired pollutants, including alkanes, esters and so on [18]. Components of alkanes and esters have also been detected in CPM [19], therefore, VOCs and CPM have intersections on those organic components. If some parts of VOCs condense into particulate state immediately after discharge, they fall within the CPM category. Meanwhile, other VOCs that do not condense rapidly after discharge do not belong to the category of CPM.

2.1.4. SO_3 and CPM

SO_3 is often confused with CPM, which is mainly due to SO_3 can easily react with water vapor in flue gas to form sulfuric acid mist [4,20] and that process is the transformation of gaseous SO_3 to the particle state. In fact, the transformation process is usually occurred among 120–140 °C [21,22], which is often higher than the emission temperature of flue gas. Namely, most of SO_3 has converted into particle state before discharge. Therefore, according to the definition of CPM, this part of SO_3 does not belong to CPM. Only SO_3, which is still in the gaseous state when discharging, is likely to fall into the category of CPM.

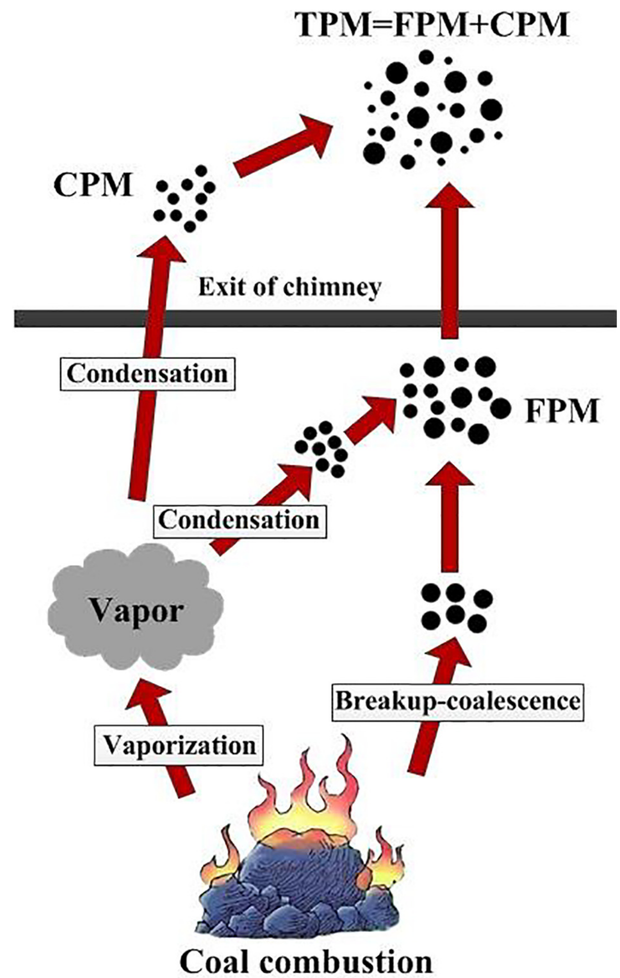

Fig. 1. Particle formation from coal combustion.

2.2. Formation mechanism of CPM

According to the definition of CPM and the basic knowledge of particulate matter, we have specially drawn the diagram of the mechanism of CPM formation, as shown in Fig. 1. In the following, the evolution of CPM in the coal-fired system is elaborated referring to Fig. 1 which has depicted the ways of the formation of FPM, CPM, and TPM. As shown in the diagram, particles are formed through two different mechanisms of "breakup–coalescence" and "vaporization–condensation" [23,24]. Those formed through "breakup–coalescence" mechanism always keep in particle state and they belong to the category of FPM. For particles formed by the mechanism of "vaporization–condensation", they can be divided into two cases: some formed by vapor condensation in the stack should belong to FPM, others condensed when flue gas is diluted and cooled immediately after its release should be called CPM. FPM and CPM are collectively called TPM and TPM is also described as the primary particles discharged directly into the environment.

In other words, the CPM is formed through the mechanism of "vaporization–condensation" [25]. This mechanism can be further subdivided into two categories: "homogeneous nucleation" [26] (condensable vapor nucleates and condenses to form particles, mainly nanoparticles measuring less than 50 nm) and "heterogeneous condensation" [27] (condensable vapor condenses on the surface of other small particles to form particles, mainly submicron particles measuring less than 1 μm). The current studies have not involved the discussion on which of these two sub-categories the CPM belongs to. In our speculation, the CPM may belong to both of them.