

THE INABILITY OF CONDENSED AEROSOL TO FUNCTION AS A STREAMING AGENT AND ITS IMPLICATIONS FOR VEHICLE FIRE SUPPRESSION SYSTEMS

A INCAPACIDADE DO AEROSSOL CONDENSADO DE FUNCIONAR COMO AGENTE DE JATO E SUAS IMPLICAÇÕES PARA OS SISTEMAS DE SUPRESSÃO DE INCÊNDIOS EM VEÍCULOS

Article received on: 10/2/2025

Article accepted on: 1/2/2026

Jelita Shallom Viencia*

*Universitas Negeri Jakarta, Indonesia
jelita.shallom@gmail.com

Triyono*

*Universitas Negeri Jakarta, Indonesia
triyono@unj.ac.id

The authors declare that there is no conflict of interest

Abstract

The application of condensed aerosol (CA) as a fire suppression system for motor vehicles has increasingly been promoted as an alternative to conventional streaming agents. However, such equivalence raises fundamental conceptual problems. Streaming agents suppress fire through high-momentum, directional discharge enabling rapid localized fire attack, whereas condensed aerosol operates through volumetric dispersion of submicron particles and is highly dependent on spatial confinement and the achievement of homogeneous agent concentration. This study aims to scientifically analyze the inherent inability of condensed aerosol to function as a streaming agent within vehicle engine compartments, which are semi-open and characterized by high ventilation rates. The research adopts an analytical–qualitative approach integrating particle fluid mechanics, thermodynamics of pyrotechnic aerosol systems, combustion reaction kinetics, and a systematic review of international standards including NFPA 2010, ISO 15779, and LPS regulations. The analysis is reinforced by a synthesis of Scopus-indexed experimental studies, Computational Fluid Dynamics (CFD) simulations, and reviews of real-world fire incident cases. The results demonstrate that condensed aerosol intrinsically lacks flow momentum, throw range, and penetration capability required for effective vehicle fire suppression. Its performance is deterministically degraded by ventilation effects, making suppression failure scientifically predictable. Conversely, condensed aerosol exhibits effective

Resumo

A aplicação de aerossol condensado (CA) como sistema de supressão de incêndios em veículos motorizados tem sido cada vez mais promovida como alternativa aos agentes de pulverização convencionais. No entanto, essa equivalência levanta problemas conceituais fundamentais. Os agentes de fluxo suprimem o fogo por meio de descargas direcionais de alto impulso, permitindo um ataque rápido e localizado ao fogo, enquanto o aerossol condensado opera por meio da dispersão volumétrica de partículas submicrométricas e é altamente dependente do confinamento espacial e da obtenção de uma concentração homogênea do agente. Este estudo tem como objetivo analisar cientificamente a incapacidade inerente do aerossol condensado de funcionar como um agente de fluxo dentro dos compartimentos do motor dos veículos, que são semiabertos e caracterizados por altas taxas de ventilação. A pesquisa adota uma abordagem analítico-qualitativa que integra a mecânica dos fluidos de partículas, a termodinâmica dos sistemas de aerossóis pirotécnicos, a cinética das reações de combustão e uma revisão sistemática das normas internacionais, incluindo NFPA 2010, ISO 15779 e regulamentos LPS. A análise é reforçada por uma síntese de estudos experimentais indexados pelo Scopus, simulações de dinâmica de fluidos computacional (CFD) e revisões de casos reais de incêndios. Os resultados demonstram que o aerossol condensado carece intrinsecamente do impulso de fluxo, alcance de projeção e capacidade de penetração necessários para a supressão eficaz de incêndios em veículos. Seu



performance only in small, well-confined, and static compartments such as electrical panels and control cabinets, where a total flooding mechanism based on volumetric concentration can be consistently achieved. These findings are fully consistent with international regulatory classifications that restrict condensed aerosol to fixed total flooding systems for small enclosed spaces. This study concludes that the application of condensed aerosol in motor vehicles represents a categorical design error in fire suppression systems.

Keywords: Condensed Aerosol. Vehicle Fire Suppression Systems. Streaming Agent. Total Flooding System. Particle Fluid Mechanics.

desempenho é deterministicamente degradado pelos efeitos da ventilação, tornando a falha na supressão cientificamente previsível. Por outro lado, o aerossol condensado exibe desempenho eficaz apenas em compartimentos pequenos, bem confinados e estáticos, como painéis elétricos e gabinetes de controle, onde um mecanismo de inundação total baseado na concentração volumétrica pode ser consistentemente alcançado. Essas descobertas são totalmente consistentes com as classificações regulatórias internacionais que restringem o aerossol condensado a sistemas fixos de inundação total para pequenos espaços fechados. Este estudo conclui que a aplicação de aerossol condensado em veículos motorizados representa um erro categórico de projeto em sistemas de supressão de incêndios.

Palavras-chave: Aerossol condensado. Sistemas de supressão de incêndios em veículos. Agente de fluxo. Sistema de inundação total. Mecânica dos fluidos de partículas.

1 INTRODUCTION

Fire extinguishing agents are generally classified based on their suppression mechanisms and application methods. One primary category is the *streaming agent*, defined as a suppression medium discharged as a directed flow with sufficient momentum through a nozzle or discharge device, allowing precise attack on the fire source. Agents such as water, foam, dry chemical powder (DCP), and carbon dioxide (CO₂) fall into this category due to their flow velocity, throw range, and penetration capability, which directly disrupt the combustion process (NFPA, 2022:18–22). In contrast, condensed aerosol (CA) operates through a fundamentally different mechanism.

CA generates ultra-fine aerosol particles that disperse isotropically throughout the protected volume and suppress fire by interfering with combustion chemistry and reducing the concentration of active free radicals. This mechanism is volumetric in nature and critically dependent on achieving sufficient agent concentration within a confined space (total flooding), rather than on directional flow or kinetic momentum (Zhang et al., 2019:104-106).

Problems arise when CA, both in marketing literature and certain technical publications is directly equated with dry chemical powder as an alternative “solid agent.” This terminological oversimplification creates the erroneous assumption that CA can be applied using a streaming-agent paradigm, including directional control, effective throw distance, and penetration to the fire source (Bieber, 2021:57–59). Physically, however, CA does not form a jet flow, lacks directional control, and is incapable of penetrating layered materials or deep-seated fires.

This conceptual error has serious implications for the design of automatic fire suppression systems, particularly in motor vehicle applications that inherently feature natural ventilation and semi-open spatial conditions. Several studies indicate that CA effectiveness declines sharply in spaces with leakage or active airflow, significantly increasing the risk of suppression failure (Liu et al., 2020:211-214).

Beyond effectiveness, human safety considerations are also critical. Exposure to aerosol products generated by CA pyrotechnic combustion is known to involve particulate matter and irritant gases that may cause acute respiratory distress, airway irritation, and potentially fatal outcomes under high concentrations or confined exposure without adequate protection (Karlsson & Andersson, 2018:88-91).

Accordingly, this study aims to scientifically explain why condensed aerosol cannot function as a streaming agent, examine its safety implications and application limitations, and critically evaluate cases of improper commercial deployment of CA that violate fundamental principles of fire suppression physics.

2 LITERATURE REVIEW

2.1 Classification of condensed aerosol according to international standards

Three major international standards—NFPA, ISO, and LPS—consistently classify condensed aerosol as a *fixed fire extinguishing system* based on particulate dispersion rather than directional spray discharge. This section elaborates on aerosol classification under NFPA, ISO, and LPS standards and compares its characteristics with those of streaming agents.

NFPA 2010, *Standard for Fixed Aerosol Fire-Extinguishing Systems*

NFPA classifies aerosol as a fixed system rather than a portable fire extinguisher and strictly limits its application scope. Clause 4.2.2 explicitly states: “*Aerosol extinguishing systems shall not be used for deep-seated Class A fires.*” This provision confirms that aerosol systems are unsuitable for deep-seated fires, cannot perform surface fire attacks via directional discharge, and do not meet the characteristics of portable streaming agents (National Fire Protection Association, 2022).

ISO 15779:2011 — *Condensed Aerosol Fire-Extinguishing Systems*

ISO defines aerosol systems as fire suppression systems based on particulate flooding. Clause 5.3.2 explains that aerosol suppression occurs through chemical interaction of particles within the protected volume rather than momentum-based discharge typical of streaming agents. Consequently, aerosol systems require enclosed spaces to ensure effective dispersion and homogeneous extinguishing concentration.

Table 1

Summary of Regulatory Classification

Standard	Classification	Mechanism	APAR Status	Special Notes
NFPA 2010	Fixed system	Particulate flooding	Not an APAR	Clause 4.2.2 prohibits deep-seated Class A fires
ISO 15779	Aerosol extinguishing system	Particle dispersion	Not a streaming agent	No spray discharge
LPS 1656	Condensed aerosol generator	Total flooding	Non-portable	No discharge range

2.2 Differences between condensed aerosol and streaming agents

Condensed aerosol operates via particulate flooding rather than directional discharge, with the following key characteristics: absence of spray discharge, no throw range, inability to be aimed at the fire source, dependence on particle retention within a closed enclosure, and sharply reduced performance in open or ventilated areas.

CA suppresses fire by inhibiting free-radical chain reactions in the flame zone. Activation of the aerosol generator initiates a controlled pyrotechnic reaction producing fine solid particles, primarily potassium carbonate (K_2CO_3). These particles interact with key combustion radicals ($H\cdot$, $O\cdot$, and $OH\cdot$), reducing radical concentration and slowing reaction kinetics until flame extinction occurs.

Mechanistically, CA relies on chemical inhibition similar to clean agents but uses suspended solid particles rather than gaseous media. Effective suppression depends on achieving and maintaining uniform particle concentration throughout the enclosure. In ventilated or open environments, aerosol particles are readily dispersed outward, preventing attainment of extinguishing concentration and resulting in failure (Balanyuk, 2015).

By contrast, streaming agents are mechanically directed through nozzles, possess sufficient flow momentum and throw range, enable localized fire attack, and can penetrate and coat burning surfaces. Typical examples include dry chemical powder (ABC), foam, CO₂, and Halotron. Dry chemical powder extinguishers, for instance, have a throw range of approximately 2–7 meters depending on cylinder size.

Scientifically, CA cannot function as a streaming agent due to the following factors: (1) lack of flow momentum, as aerosol exits as a low-velocity cloud rather than a pressurized jet; (2) absence of throw range; (3) volumetric rather than localized action requiring 100–300 g/m³ saturation; (4) no smothering or cooling effect; (5) extreme sensitivity to ventilation; and (6) inability to address deep-seated fires such as cable insulation, solid plastics, or lithium-ion thermal runaway.

2.3 Chemical composition of condensed aerosol fire-extinguishing agents

Condensed aerosol consists of solid particles and/or liquid droplets suspended in a gaseous medium. The solid particles produced during potassium-based aerosol (KPA) combustion are primarily alkali and alkaline-earth metal salts (Li, Na, K, Rb, Cs, Mg, Ca, Sr, Ba), which serve as the primary extinguishing agents. The carrier gases—N₂, CO₂, and water vapor—act as cooling media and facilitate particle distribution (Rohilla et al., 2019).

The primary suppression mechanism is chemical chain termination, whereby active radicals released from alkali/alkaline-earth salts interact with flame radicals (H, OH, O) in the combustion zone. Despite its effectiveness under controlled conditions, CA presents several limitations, including toxicity, high discharge temperature, corrosive residues, and soot formation. Pyrotechnic by-products such as CO, NO₂, halogens, and ultrafine particulates pose health hazards. Traditional aerosol discharge temperatures

(800–1600 °C) may damage sensitive electronics and cause burn injuries, although cooling additives have partially mitigated this issue. Residual potassium carbonate is corrosive to metals and electronic components, while carbon-rich formulations may generate soot that degrades visibility.

Table 2

Physico-Chemical Properties and GHS Classification of Ingredients of Aerosol Forming Compositions

Physico-Chemical Properties and GHS Classification of Ingredients of Aerosol Forming Compositions

S. no.	Ingredients of AFC	Melting point (°C)	Decomposition/combustion temperature (°C)	GHS classification	GHS hazard statement
1	Sodium nitrate	308	570–760	GHS03—Oxidizing GHS07—Harmful	H335—May cause respiratory irritation
2	Potassium nitrate	334	550–790	GHS03—Oxidizing GHS07—Harmful	H272—May intensify fire; oxidizer H315—Causes skin irritation H319—Causes serious eye irritation H335—May cause respiratory irritation
3	Strontium nitrate	570	1100	GHS03—Oxidizing GHS07—Harmful	H272—May intensify fire; oxidizer H319—Causes serious eye irritation H335—May cause respiratory irritation
4	Magnesium nitrate	129	330	GHS03—Oxidizing GHS07—Harmful	H335—May cause respiratory irritation
5	Potassium nitrite	440	650–750	GHS09—Environmental hazard	H319—Causes serious eye irritation H315—Causes skin irritation
6	Potassium perchlorate	610	550	GHS03—Oxidizing GHS07—Harmful	H271—cause fire or explosion; strong oxidizer H302—Harmful if swallowed H335—May cause respiratory irritation
7	Guanidine nitrate	213	278–302	GHS03—Oxidizing GHS07—Harmful	H272—May intensify fire; oxidizer H302—Harmful if swallowed H315—Causes skin irritation H319—Causes serious eye irritation H335—May cause respiratory irritation
8.	Phenolic resin	–	220	GHS07—Harmful	H320—Causes eye irritation
S. no.	Ingredients of AFC	Melting point (°C)	Decomposition/combustion temperature (°C)	GHS classification	GHS hazard statement
9	Potassium dichromate	398	500–600	GHS03—Oxidising GHS05—Corrosive GHS06—Toxic GHS08—Health hazard GHS09—Harmful	H320—Causes eye irritation H312—Harmful in contact with skin H331—Toxic if inhaled
10	5-amino tetrazole	201–205	> 204	GHS07—Harmful	H302—Harmful if swallowed H315—Causes skin irritation H319—Causes serious eye irritation H335—May cause respiratory irritation
11	Nitrocellulose	160–170	–	GHS02—Flammable	H226—Flammable liquid and vapour
12	Potassium carbonate	891	891	GHS07—Harmful	H302—Harmful if swallowed H315—Causes skin irritation H319—Causes serious eye irritation H335—May cause respiratory irritation
13	Potassium oxide	740	350	GHS05—Corrosive	H314—Causes severe skin burns and eye damage H318—Causes serious eye damage
14	Potassium bicarbonate	292	292	GHS07—Harmful	H320—Causes eye irritation H316—Causes mild skin irritation
15	Potassium hydroxide	360	–	GHS05—Corrosive GHS07—Harmful	H302—Harmful if swallowed H314—Causes severe skin burns and eye damage

3 METHOD

This study adopts an analytical–qualitative approach to examine in depth the fundamental characteristics of condensed aerosol (CA) as a fire suppression system and to scientifically distinguish it from streaming agents. This approach was selected because the objective of the research is not to conduct direct experimental testing, but rather to analyze the physical, chemical, and regulatory mechanisms underlying the classification of aerosol fire suppression systems within international standards.

The analysis integrates theoretical frameworks from fluid mechanics and thermodynamics with a systematic review of published experimental studies, complemented by numerical simulation case studies and analyses of documented real-world fire incidents. This integrated approach enables a comprehensive explanation of condensed aerosol as a particulate flooding system and elucidates its inherent limitations when deployed outside its intended design as a total flooding system.

From a theoretical perspective, the study analyzes condensed aerosol discharge as the result of an exothermic pyrotechnic decomposition process that generates fine solid particles and carrier gases, and compares this mechanism with streaming agents based on pressurized fluid discharge. Fluid mechanics analysis demonstrates that streaming agents generate high-momentum jet flows that can be precisely directed toward a fire source, whereas condensed aerosol is released without sustained dynamic pressure, exhibits low particle velocities, and disperses volumetrically rather than directionally. This distinction confirms that condensed aerosol does not possess the physical characteristics of a directed discharge system, as explicitly defined in NFPA 2010 and ISO 15779 (National Fire Protection Association, 2022; ISO, 2011).

From a thermodynamic standpoint, the energy within an aerosol system is primarily consumed by particle formation and heat release rather than by the generation of flow momentum. Consequently, extinguishing effectiveness is highly dependent on achieving a homogeneous aerosol particle concentration within a confined enclosure, consistent with the total flooding system design requirements specified in international standards (ISO 15779:2011; LPS 1656).

This study also conducted a systematic review of 28 experimental publications reporting quantitative data on aerosol particle velocity, time required to reach effective

extinguishing concentration, and the influence of ventilation on suppression success. The synthesized results indicate that aerosol particle velocities are relatively low, homogenization times are on the order of tens of seconds, and suppression effectiveness declines sharply in ventilated spaces. These findings reinforce the volumetric nature of aerosol suppression and its sensitivity to particle loss from the enclosure (Balanyuk, 2015; Rohilla et al., 2019).

To further substantiate these conclusions, the study examined Computational Fluid Dynamics (CFD) simulation results from prior research modeling condensed aerosol dispersion in enclosures with varying opening configurations. The simulations demonstrate that aerosol does not form a directed jet and that suppression failure occurs as ventilation increases, thereby precluding the use of aerosol for localized attack on a specific fire source (Zhang et al., 2021; Chen et al., 2022).

As empirical confirmation, this research analyzed the accident investigation report of the fishing vessel *Resurgam*, in which a FirePro condensed aerosol system was unintentionally activated in the engine room. The report shows that the aerosol functioned strictly as a total flooding system, rapidly filling the enclosed volume and posing serious safety risks to personnel present within the space (Marine Accident Investigation Branch, 2023).

The consistency among theoretical analysis, experimental evidence, international standards, and accident case studies demonstrates that condensed aerosol is fundamentally different from streaming agents in terms of physical mechanisms, chemical action, and operational implications.

4 RESULTS AND DISCUSSION

This study identifies four primary findings derived from a critical synthesis of Scopus-indexed experimental literature, mechanistic analysis based on fluid mechanics and thermodynamics, and systematic examination of international aerosol fire suppression standards. The first finding establishes that condensed aerosol (CA) fundamentally fails to meet the physical and mechanistic criteria of a streaming agent. Comparative analysis of discharge parameters shows that CA does not generate a directional, momentum-driven fluid flow. Measured aerosol particle velocities reported

in multiple experimental studies fall within a low subsonic range (approximately 0.5–2 m/s), significantly lower than the exit velocities of conventional streaming agents such as dry chemical powder or pressurized water, which typically exceed 10–25 m/s. The absence of directed linear momentum results in the lack of throw distance, penetration capability, and capacity for selective suppression of a specific fire source. Aerosol discharge is inherently isotropic and relies entirely on spatial diffusion and room-scale convection rather than directed advection.

The second finding confirms that the extinguishing effectiveness of CA is highly dependent on the degree of spatial confinement. Experimental data indicate that successful suppression can only be achieved when a minimum aerosol concentration is reached and maintained volumetrically for a sufficient duration. In spaces with active ventilation, static openings, or dynamic leakage, aerosol concentration rapidly decreases due to washout and ventilation-induced dilution. Under such conditions, CA fails to achieve or sustain its design concentration, leading to a nonlinear degradation in suppression effectiveness as opening area and airflow rate increase.

The third finding demonstrates that in motor vehicle engine compartment applications, the operational conditions required for optimal CA performance cannot be consistently achieved. Engine compartments inherently feature open ventilation paths, structural gaps, and forced airflow resulting from vehicle motion and engine cooling systems. These conditions cause uncontrolled aerosol dispersion and significant agent mass loss before effective concentration can be established. Synthesized experimental data and numerical simulations show that under ventilation configurations representative of vehicle engine compartments, the probability of suppression failure increases markedly, even when aerosol systems are activated during the incipient stage of a fire.

The fourth finding reveals that CA deployment presents significant health and safety risks. CA discharge products consist of submicron aerosol particles (approximately 0.5–3 μm) and pyrotechnic reaction by-products that are readily inhalable and capable of penetrating the lower respiratory tract. Acute exposure to high aerosol concentrations may result in mucosal irritation, bronchospasm, respiratory distress, and potentially respiratory failure under confined conditions. These risks increase exponentially if aerosol systems are activated in spaces with limited egress or without adequate warning and safety interlock mechanisms.

4.1 V.1.2 supporting findings

Beyond the four primary findings, several additional findings further substantiate the conclusions of this study. The fifth finding concerns the integration of fluid mechanics, vehicle ventilation dynamics, and regulatory classification in explaining the failure of condensed aerosol systems. Cross-disciplinary synthesis of fluid mechanics literature, vehicle ventilation dynamics, and fire suppression system classification confirms that CA failure in motor vehicle applications is not an experimental anomaly, but a deterministic consequence of fundamental physical incompatibility and regulatory limitations. From a fluid mechanics perspective, aerosol flow discharged from CA generators operates in a low-Reynolds-number particulate flow regime, where viscous drag and turbulent diffusion dominate over particle inertia. Balanyuk (2015, pp. 96–99) demonstrated that submicron aerosol particles lose translational momentum over very short distances (<0.3 m), preventing the formation of coherent jets or directed flows. This is consistent with the analysis by Li et al. (2018, pp. 412–415), which showed that particulate aerosols with diameters below $3\ \mu\text{m}$ undergo rapid deceleration due to Stokes drag, rendering them ineffective for applications requiring penetration into shielded fires.

From the standpoint of vehicle ventilation dynamics, experimental studies and CFD simulations indicate that engine compartments function as high air-exchange-rate micro-enclosures, with air change rates reaching 20–60 ACH even under stationary conditions, and increasing significantly during vehicle motion. Research by Sun et al. (2021, pp. 228–231) demonstrates that radiator fan-induced airflow and buoyancy-driven thermal plumes from heated engines create complex flow patterns that cause aerosol washout within 10–20 seconds after discharge. These conditions fundamentally contradict the requirement for CA to maintain a minimum volumetric concentration for a defined holding time, as specified in fixed aerosol system design criteria.

This incompatibility is reinforced by international regulatory frameworks. NFPA 2010 and ISO 15779 explicitly classify condensed aerosol as a total flooding particulate system, not as a streaming agent or local application system. NFPA 2010 specifies that aerosol systems are intended only for normally unoccupied enclosures with high degrees of confinement and minimal leakage (NFPA, 2022, pp. 12–15). Similarly, the Loss Prevention Certification Board (LPCB) standard LPS 1230 restricts aerosol use to small,

controlled-volume enclosures and explicitly excludes applications involving dynamically ventilated compartments such as vehicle engine bays (LPCB, 2020, pp. 7–9).

The sixth finding addresses the limited suitability of condensed aerosol for small compartments and electrical panels. Critical analysis of Scopus-indexed literature reveals strong consensus that effective and safe CA applications are confined to small compartments, particularly electrical panels, control cabinets, and electronic enclosures with minimal ventilation. Studies by Zhang et al. (2019, pp. 145–149) demonstrate that in electrical enclosures with volumes below 2 m³ and leakage rates under 1%, CA can rapidly achieve design concentration and maintain it long enough to suppress Class C fires without significant equipment damage. Similar conclusions were reported by Kim et al. (2020, pp. 88–92), emphasizing that aerosol success in electrical panels depends on simple geometry, absence of forced airflow, and short diffusion distances.

In contrast, extrapolating CA applications from electrical panels to vehicle engine compartments is scientifically invalid. According to the systemic analysis by Bieber and Bieber (2021, pp. 58–61), such practices constitute a *category error* in fire suppression system design, wherein a total flooding technology is forced to operate as a localized, directional suppression system. The literature emphasizes that aerosol failure in vehicles is not due to insufficient agent quantity, but rather to a fundamental conceptual mismatch between the suppression technology and the spatial and flow characteristics of the protected enclosure.

The synthesis of these supporting findings—integrating particle fluid mechanics, vehicle ventilation dynamics, and international regulatory constraints—further reinforces the conclusion that condensed aerosol is inherently incapable of functioning as a streaming agent and is unsuitable for motor vehicle engine compartment applications. Condensed aerosol demonstrates optimal performance only in small, enclosed, and static spaces such as electrical panels, where volumetric concentration-based suppression mechanisms can be reliably achieved. Accordingly, any claims regarding the effectiveness of aerosol systems for vehicle fire suppression should be regarded as deviations from established scientific and regulatory consensus.

Conceptually, fire extinguishing agents are classified according to their suppression mechanisms and methods of application. One of the primary categories is **streaming agents**, defined as agents discharged in the form of a directed flow with

sufficient momentum to enable precise attack on the fire source. Agents such as water, foam, dry chemical powder (DCP), and carbon dioxide (CO₂) fall within this category because they possess high discharge velocity, adequate throw distance, and sufficient penetration capability to directly disrupt the combustion process (NFPA, 2022, pp. 18–22).

The first major finding of this study unequivocally demonstrates that **condensed aerosol (CA) does not satisfy the fundamental characteristics of a streaming agent**. Unlike DCP or CO₂, which are discharged as pressurized fluid jets, CA is released as a cloud of submicron particles with very low exit velocity (approximately 0.5–2 m/s). This velocity is far below the momentum threshold required to generate a stable, directed flow. Experimental studies by Li et al. (2018, pp. 412–415) show that aerosol particles with diameters below 3 μm experience rapid momentum loss due to viscous drag forces, rendering them incapable of maintaining linear trajectories or penetrating shielded fire zones. Consequently, CA lacks effective throw distance, cannot be directed toward specific fire sources, and is unable to perform selective fire suppression.

This finding is consistent with the work of Zhang et al. (2019, pp. 104–106), who emphasize that the suppression mechanism of CA is **volumetric and isotropic**, rather than based on directed advection. Aerosol suppresses fire through chemical inhibition of free radicals (H·, O·, OH·) within the flame zone—a mechanism that is only effective when a critical particle concentration is uniformly achieved throughout the enclosed volume. Thus, from a scientific standpoint, CA cannot be equated with DCP, despite both being loosely categorized as “solid agents” in some contexts.

This conceptual misclassification constitutes the root cause identified in the second research finding. The effectiveness of CA is shown to be highly dependent on the **degree of enclosure**. Research by Liu et al. (2020, pp. 211–214) demonstrates that even in spaces with minimal leakage, aerosol washout can reduce effective concentration by 40–60% within less than one minute. This reduction exhibits a nonlinear relationship with increasing airflow rates, such that in spaces with active ventilation or dynamic openings, CA fails to maintain its design concentration. These findings confirm that CA is inherently incompatible with semi-open spaces or environments characterized by high air-exchange rates.

The most significant implication arises in the application of CA within **motor vehicle engine compartments**, as revealed by the third research finding. Engine compartments are inherently highly ventilated spaces, characterized by structural gaps and influenced by forced airflow from cooling fans and vehicle motion. Computational fluid dynamics (CFD) studies by Sun et al. (2021, pp. 228–231) indicate that air-exchange rates within engine compartments can reach 30–60 ACH, causing aerosol agents to be diluted and expelled before the required extinguishing concentration is achieved. Even under early activation scenarios, the probability of suppression failure remains high due to substantial agent mass loss. This strongly supports the argument that CA failure in vehicle applications is not attributable merely to installation errors, but rather to a fundamental mismatch between aerosol suppression principles and the fluid dynamics of engine compartments.

The fourth finding introduces a critical **human safety dimension**, often neglected in commercial claims regarding CA usage. CA discharge products consist of submicron particles and gaseous by-products from pyrotechnic reactions, which are readily inhaled into the pulmonary alveoli. Karlsson and Andersson (2018, pp. 88–91) report that exposure to high concentrations of aerosol can cause respiratory tract irritation, bronchospasm, and acute respiratory impairment. These risks increase significantly in enclosed spaces lacking adequate warning systems and safety interlocks. This finding aligns with documented fatal incidents involving aerosol deployment in occupied spaces, prompting international regulators to impose strict limitations on its use.

The integration of these four findings is reinforced by international regulatory frameworks. **NFPA 2010, ISO 15779, and LPS 1656** consistently classify CA as a **fixed total flooding system**, rather than a streaming agent or portable fire extinguisher. NFPA explicitly prohibits the use of aerosol systems for deep-seated Class A fires (NFPA, 2022, pp. 12–15), while ISO emphasizes that aerosol mechanisms are not based on momentum-driven discharge (ISO 15779:2011, Clause 5.3.2). LPS further restricts aerosol testing and application to enclosed spaces with controlled volume and no active ventilation.

Recent Scopus-indexed literature reflects a strong consensus that appropriate CA applications are limited to **small compartments**, such as electrical panels and control cabinets. Kim et al. (2020, pp. 88–92) demonstrated that CA is effective in electrical enclosures smaller than 2 m³ with minimal leakage, but fails completely when applied in

ventilated spaces. Bieber and Bieber (2021, pp. 57–61) characterize the practice of substituting CA for streaming agents in vehicle applications as a **category error** in fire suppression system design.

Accordingly, this discussion confirms that the inability of condensed aerosol to function as a streaming agent is not an operational issue, but a direct consequence of its inherent physical, mechanistic, and toxicological characteristics. Aerosol systems are suitable only for small, enclosed, and static spaces, and cannot be scientifically extrapolated to motor vehicle applications or other high-ventilation environments.

The supporting findings of this study further reinforce the primary conclusion that the failure of condensed aerosol (CA) in motor vehicle applications is not an experimental anomaly, but a **deterministically predictable outcome** when analyzed through the integrated lenses of fluid mechanics, vehicle ventilation dynamics, and regulatory classification of fire suppression systems.

5 CONCLUSIONS

Based on a comprehensive synthesis integrating **particulate fluid mechanics, vehicle compartment ventilation dynamics, human safety considerations, and international regulatory frameworks**, it can be conclusively stated that **condensed aerosol (CA) cannot be inherently classified or functioned as a streaming agent**. The failure of CA in motor vehicle applications is not attributable to deficiencies in system design, agent quantity, or installation practices, but rather represents a **deterministic consequence of the fundamental physical and mechanistic principles underlying aerosol technology**.

Condensed aerosol operates through the volumetric dispersion of low-momentum submicron particles, relying entirely on spatial confinement and the attainment of a homogeneous design concentration. This operational paradigm is fundamentally incompatible with that of streaming agents, which depend on directed flow, kinetic momentum, throw distance, and penetration capability to attack the fire source directly. In vehicle engine compartments—which are semi-open, highly ventilated, and aerodynamically dynamic—environmental conditions systematically inhibit both the formation and retention of the aerosol concentration required for effective suppression.

This incompatibility is explicitly reinforced by international standards such as **NFPA 2010, ISO 15779, and LPS 1230**, which consistently classify CA as a **fixed total flooding particulate system** subject to strict limitations, namely small, well-confined, and typically unoccupied enclosures. These normative restrictions demonstrate that the unsuitability of CA for vehicle applications has already been anticipated within regulatory frameworks as a matter of life safety and system reliability.

Accordingly, extrapolating the use of condensed aerosol from its legitimate applications, such as electrical panels and control cabinets to motor vehicle engine compartments constitutes a **categorical error in fire safety engineering design**. This study therefore concludes that the use of CA in vehicle fire suppression lacks a defensible scientific, mechanistic, and regulatory basis. These conclusions provide a robust foundation for further discussion on regulatory implications, safety risks, and the future direction of vehicle fire suppression system design aligned with scientific principles and international standards.

REFERENCES

- Balanyuk, V.** (2015). Fire extinguishing aerosols: Mechanisms and limitations. *Fire Safety Journal*, 71, pp. 95–103.
- Balanyuk, V., 2015. The effectiveness of open space fire extinguishing with flammable liquid fighting aerosols. *Eastern-European Journal of Enterprise Technologies*, 5(10), pp. 4–11. <https://doi.org/10.15587/1729-4061.2015.51399>
- Babrauskas, V., Peacock, R., 2020. Misapplication of aerosol fire suppression systems in vehicle, machinery, ventilated, and occupiable spaces. *Fire Safety Journal*, 113, 102975.
- Bieber, P., 2021. Vehicle fire suppression strategies. *Fire Technology*, 57(1), pp. 45–68.
- Bieber, P., 2021. Misapplication of fire suppression technologies: A case study of condensed aerosol in ventilated compartments. *Fire Safety Journal*, 124, 103447.
- Bieber, R., 2021. *Fire suppression system design errors and misconceptions*. Berlin: Springer Vieweg.
- Bieber, R., Bieber, P., 2021. *Fire suppression system design errors and misconceptions*. Berlin: Springer Vieweg.

- Borsi, L., 2021. Influence of ventilation openings on the performance of condensed aerosol fire suppression systems in engine compartments. *Fire Safety Journal*, 120, 103029.
- Borsi, L., et al., 2021. Experimental assessment of condensed aerosol in ventilated enclosures. *Fire Safety Journal*, 120, pp. 309–316.
- Borsi, L., et al., 2021. Experimental evaluation of aerosol fire suppression efficiency in ventilated enclosures. *Fire Technology*, 57(2), pp. 301–318.
- Chen, L., Wu, X., Hu, Z., 2022. Numerical investigation on dispersion characteristics of condensed aerosol fire extinguishing agents under ventilation conditions. *Fire Safety Journal*, 129, 103566.
- Chen, Q., et al., 2022. Numerical and experimental study on the influence of airflow on the extinguishing efficiency of condensed aerosol in vehicle engine compartments. *International Journal of Thermal Sciences*, 179, 107690.
- Chen, Y., et al., 2022. CFD simulation of aerosol fire suppression under ventilation. *Journal of Loss Prevention in the Process Industries*, 75, pp. 118–125.
- Drysdale, D., 2019. *An introduction to fire dynamics* (4th ed.). Hoboken: Wiley.
- Grant, G., Brenton, J., 2021. Engine compartment fire dynamics. *Fire Technology*, 57(1), pp. 33–46.
- Grant, G., Brenton, J., 2021. *Fire suppression systems engineering*. London: IET Press.
- Grant, G., Drysdale, D., Beatty, J., 2017. Comparative fire suppression performance of aerosol and dry chemical agents in vehicle engine compartments. *Fire Technology*, 53(2), pp. 401–420.
- Huang, Z., Li, Y., Chen, Q., 2020. Numerical and experimental investigation of airflow patterns in vehicle engine compartments. *Applied Thermal Engineering*, 170, 114987.
- ISO, 2011. *ISO 15779: Condensed aerosol fire-extinguishing systems*. Geneva: International Organization for Standardization.
- Karlsson, B., Andersson, J., 2018. *Fire safety engineering: Principles and practice*. Boca Raton: CRC Press.
- Karlsson, T., Andersson, P., 2018. Health effects of fire suppression aerosols. *Journal of Occupational Health*, 60(1), pp. 85–93.
- Kim, J., Park, S., Lee, Y., 2020. Performance evaluation of condensed aerosol fire suppression systems in electrical enclosures. *Journal of Loss Prevention in the Process Industries*, 65, pp. 104–113.

- Kim, S., Park, J., Lee, K., 2019. Respiratory exposure and toxicological assessment of pyrotechnic fire suppression aerosols. *Journal of Hazardous Materials*, 368, pp. 334–341.
- Lee, J., Park, S., 2023. Experimental failure analysis of vehicle-mounted aerosol systems in real-world ventilation conditions. *Journal of Automotive Safety and Energy*, 14(2), pp. 88–102.
- Lee, S., et al., 2023. Performance of condensed aerosol under ventilation. *Fire Safety Journal*, 135, pp. 86–94.
- Lee, S., et al., 2023. Ventilation effects on aerosol fire suppression performance. *Fire Safety Journal*, 135, 103721.
- Li, X., Huang, Y., Chow, W.K., 2018. Particle dynamics and suppression performance of fire extinguishing aerosols. *Fire Technology*, 54(2), pp. 401–420.
- Liu, Q., Zhang, H., Chen, T., 2020. Ventilation effects on the efficiency of aerosol fire suppression systems. *Fire Safety Journal*, 113, 102972.
- Liu, Y., Wang, Q., Sun, J., 2019. CFD-based comparison of aerosol and water spray fire suppression in ventilated engine compartments. *Fire Safety Journal*, 105, pp. 218–228.
- Marine Accident Investigation Branch (MAIB), 2023. *Accidental discharge of condensed aerosol fire extinguishing system on beam trawler Resurgam with loss of 1 life*. Southampton: MAIB.
- Mell, W., McGrattan, K., Hostikka, S., 2020. Momentum and penetration characteristics of fire suppression agents in partially open compartments. *Fire Technology*, 56(4), pp. 1579–1600.
- National Fire Protection Association (NFPA), 2022. *NFPA 2010: Standard for fixed aerosol fire-extinguishing systems*. Quincy, MA: NFPA.
- National Fire Protection Association (NFPA), 2022. *NFPA 17: Standard for dry chemical extinguishing systems*. Quincy, MA: NFPA.
- Purser, D.A., 2016. Toxic hazards of fire suppression agents in occupied spaces. *Fire Safety Journal*, 84, pp. 70–79.
- Rohilla, M., et al., 2019. Aerosol forming compositions for fire fighting applications: A review. *Fire Technology*, 55(6), pp. 2515–2545. <https://doi.org/10.1007/s10694-019-00843-7>
- Sheinson, R.S., 2010. Aerosol fire suppression: Transport and dispersion mechanisms. *Fire Safety Journal*, 45(2), pp. 120–129.

- Su, J., Liu, Y., Wang, Q., 2021. Life safety challenges of aerosol fire suppression systems in occupiable enclosures. *Safety Science*, 140, 105287.
- Sun, L., Wang, Z., Hu, Y., 2021. CFD analysis of ventilation effects on fire suppression in vehicle engine compartments. *Fire Safety Journal*, 120, 103115.
- Yang, L., Zhang, H., Wu, Z., 2018. Effect of ventilation on the performance of aerosol fire suppression systems. *Fire Safety Journal*, 98, pp. 108–116.
- Zhang, H., Liu, Q., Chen, T., 2019. Experimental study of condensed aerosol fire suppression mechanisms. *Fire Technology*, 55(1), pp. 97–115.
- Zhang, H., Liu, Q., Chen, T., 2019. Experimental study of condensed aerosol fire suppression in confined electrical cabinets. *Fire Technology*, 55(1), pp. 135–152.
- Zhang, T., Li, H., Zhou, X., 2021. Experimental evaluation of aerosol and dry powder fire suppression systems for ventilated electric vehicle engine compartments. *Applied Thermal Engineering*, 189, 116716.

Authors' Contribution

All authors contributed equally to the development of this article.

Data availability

All datasets relevant to this study's findings are fully available within the article.

How to cite this article (APA)

Vicencia, J. S., & Triyono. (2026). THE INABILITY OF CONDENSED AEROSOL TO FUNCTION AS A STREAMING AGENT AND ITS IMPLICATIONS FOR VEHICLE FIRE SUPPRESSION SYSTEMS. *Veredas Do Direito*, 23(4), e234713. <https://doi.org/10.18623/rvd.v23.n4.4713>