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Three condensation paths of exhaust and its five effects on exhaust gas recirculation (EGR) cooler fouling and thermal performance: A review

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ABSTRACT

Fouling has limited the evolution of compact heat exchangers (represented by EGR cooler) to smaller and more efficient sizes, an important reason is the unclear mechanism of the effect of exhaust gas condensation on fouling and thermal performance. This paper reviews the effects of hydrocarbon vapor, water vapor and acid vapor condensation on EGR cooler fouling and thermal performance from 1998 to 2023. Three paths of vapors condensation can occurr: interaction with particles, homogeneous nucleation and interaction with fouling. Beneficial effect (3) and harmful effects (2) to EGR cooler thermal performance have identified: filling, removal and chemical are beneficial effects whereas adhesion and nucleation are harmful effects. Three pathways and five effects play a key role on the composition, the mass, the thickness, density, the morphology and thermal resistance of fouling layer. The involvement level of sub-paths and contribution degree of sub-effects of vapor condensation under different boundary conditions, standard database, holistic model and the effect of renewable synthetic fuels on fouling and thermal performance can be further explored. The results will help researchers to understand the logical relationship between exhaust vapor condensation and fouling and thermal performance from the new perspective of condensation.

1. Introduction

Compact heat exchangers are widely used in industry due to their small size, high heat transfer performance and wide range of types [1–4]. A typical application is the EGR cooler fitted to automobiles, which cools the exhaust gas from 600-800 °C to100 °C after combustion and reintroduces it into the intake tract to reduce nitrogen oxide (NOx) emissions [5–8]. However, because the exhaust gas is rich in particulate matter and multiple vapors after combustion, the EGR cooler will generate fouling under complex physical and chemical effects.

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As shown in Fig. 1, particles are deposited to the inner wall of the cooling tube under the action of thermophoresis, gravity and electrostatic force, etc., while the vapor in the exhaust gas also condenses to the inner wall of the cooling tube under suitable conditions, and the deposited particles and condensate together constitute the fouling. In terms of heat transfer path, in the absence of fouling, the thermal resistance is only the convective heat transfer resistance from the central airflow to the inner wall of the cooling tube ①$R_{conv-gas}$ and the cooling tube wall's own thermal resistance ③ $R_{cond-wall}$; However, when there is fouling, fouling induced by ②$R_{cond\text{-}fouling}$ increases the total thermal resistance of heat transfer and reduces the heat transfer performance of the heat exchanger [9–11]; at the same time, fouling also increases the pressure drop and the EGR control strategy deviates from the normal level [9–11]. In the most severe cases, fouling clogs the flow piping and makes the EGR cooler completely ineffective [12,13], which leads to high levels of NOx emissions, which defeats the original purpose of applying EGR cooling technology. To cope with these problems, designers are often forced to design larger EGR coolers to counteract the harm caused by fouling. Therefore, the fouling problem limits the development of compact heat exchangers to be smaller and more efficient; especially when one side of the heat exchanger is a multiphase flow containing particulate matter and vapor, the fouling problem cannot be taken lightly.

The composition of the exhaust gas after engine combustion is very complex. Still, it can be divided into solid, liquid particulate matter, and gaseous vapor regarding phase state. The composition of the EGR cooler fouling is also very complex, but it has been reported that the two major sources of fouling are the particulate matter and condensate [14,15], as shown in Fig. 1. Among them, the deposition mechanism of particulate matter from exhaust gas deposition to the EGR cooler surface has been the subject of numerous research papers [16–32] and review papers [33–39], and significant progress has been made; However, research on the topic of vapor condensation in EGR coolers has been relatively weak, although in recent years some studies have been done on the effects of vapor condensation on fouling and cooler thermal performance [40–46].

Among the published reviews, Hoard et al. [33] proposed the first review in the field that focuses on describing what fouling is and the process of fouling establishment, stabilization, recovery and removal, Abd-Elhad et al. [34,36] focus on the characterization of particulate matter in exhaust gases and techniques to mitigate fouling, Abarham et al. [35] systematically reviews the mechanisms of deposition and removal of particulate matter and compares order of magnitude of these mechanisms, Kumar et al. [37] briefly reviewed the control parameters of the system, such as flow rate, fuel type and effect on fouling, Han et al. [38] further reviewed the deposition and removal mechanisms of fouling based on the Abarham et al. [35] and proposed a conceptual model to explain the whole process, while Paz et al. [39] focused on the mathematical model of the fouling process review.

In brief, these different reviews focuses mainly on three aspects: (i) control parameters on fouling, (ii) deposition and removal mechanism of particles, (iii) modelling of the fouling process; it is not difficult to see that the focus of the past reviews is the particulate matter deposition or fouling generation process, and vapor condensation does not seem to be treated properly, and so far to date, no paper has systematically described the relationship between vapor condensation, fouling and thermal performance in EGR coolers, which may be one of the fundamental reasons why the fouling problem in EGR coolers has not been completely solved. Compared with previously published reviews, this review has the following advantages: (i) it presents a systematic review of a new and complete logical chain, i.e., "vapor condensation-fouling-thermal performance"; (ii) it presents an exhaustive diagram of the vapor condensation path in EGR coolers; (iii) the most complete theoretical system of the effect of vapor condensation on fouling and thermal performance in EGR coolers is presented.

This review paper systematically analyses the research on vapor condensation in EGR cooler fouling over the past 25 years (1998–2023), summarizes their consensus and disagreement, analyzes what caused these disagreements, provides a comprehensive statement of what role exhaust gas condensation plays in the EGR cooler fouling and heat transfer process, and identifies branch topics for further research. This paper contributes to a more systematic and rapid understanding of the relationship between exhaust condensation, fouling and heat transfer in EGR cooler fouling for new researchers and also provides new sub-topics for existing researchers to expand upon.

2. Vapor condensation in EGR cooler

2.1. Principle

When the saturation ratio of the vapor of a species exceeds 1, the species will change of the state from the supersaturated gaseous state into the liquid state, a process known as condensation. The saturation ratio is the ratio of the partial pressure of the species to the saturation vapor pressure of the same species at a given temperature, where the partial pressure depends on the concentration of the species and the saturation vapor pressure depends on the temperature [41,44,47–49]. Thus, both higher concentrations and lower

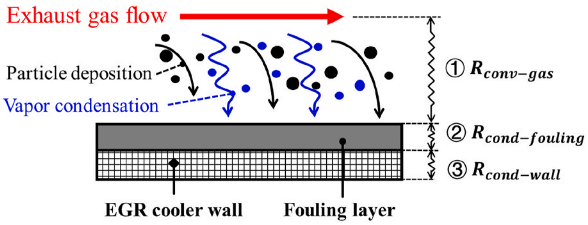

Fig. 1. Schematic diagram of thermal resistance of EGR cooler fouling, particle deposition and exhaust vapor condensation (black ball represents particles, and blue ball represents condensate). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

temperatures are more favorable for condensation.

2.2. Three paths for exhaust vapor condensation and their priority

Researchers have extensively researched the types of vapor condensation [35,40,47,49–51]. Fig. 2 summarizes a complete and detailed vapor condensation pathway. Condensation ① is that the vapor in the central area can be directly condensed on the surface of the particulate matter, or can nucleate with tiny particles through heterogeneous nucleation; Condensation ② is that vapor in the central region and boundary layer into liquid or solid particles through homogeneously nucleation; condensation ③ means that the vapor in the boundary layer can condense on/into the fouling; Condensation ③(a) and ③(b) is the way in which the vapor in the boundary layer pass through the highly porous fouling surface and condense under the fouling, where condensation ③(b) is condensed on the existing liquid condensate surface, while condensation ③(a) is condensed on the inner wall of the cooling pipe; Condensation ③(a) is often the early stage of EGR cooler operation, that is, the period without any pollution, and when the EGR cooler runs for a period of time, a layer of hydrocarbon liquid film is formed on the inner wall of the cooling pipe, and the condensation mode changes from condensation ③(a) to condensation ③(b). Condensation ③(c) is that the vapor in the boundary layer can condense directly on the surface of fouling. When the vapor concentration in the boundary layer decreases due to condensation, vapor in the central region supplements the boundary layer by diffusion. During the entire condensation process, the temperature sequence is as follows: $T_{center\ gas} > T_{surface\ of\ fouling} > T_{surface\ of\ condensate} > T_{inner\ wall} > T_{outer\ wall} > T_{coolant}$; In terms of the tendency of vapor condensation, it is completely opposite to the temperature sequence; that is to say, the closer to the central temperature zone, the smaller the tendency of vapor to condense, and the closer to the inner wall of the cooling wall, the greater the tendency of vapor to condense, and their condensation tendency follows the following order: $Tendency_{inner\ wall} > Tendency_{surface\ of\ condensate} > Tendency_{surface\ of\ fouling} > Tendency_{center\ gas}$. However, the vapor diffusion direction is from the central area to the inner wall of the cooling tube from the perspective of the spatial diffusion path, the location priority of condensation follows the following order: $Priority_{center\ gas} > Priority_{surface\ of\ fouling} > Priority_{surface\ of\ condensate} > Priority_{inner\ wall}$. Therefore, although the inner wall temperature of the cooling wall is the lowest and the condensation tendency is the largest, it is the most inferior position; On the contrary, although the temperature of the central airflow is the highest and the tendency of condensation is the smallest, it is the most advantageous in position. From the center area to the inner wall of the cooler wall, condensation can occur once the temperature is lower than the dew point temperature (or saturation ratio exceeding 1).

Homogeneous nucleation can theoretically occur when the saturation ratio exceeds 1, but in practice, it becomes significant when it exceeds 3 [52]. Since volatile vapors in the exhaust of an engine do not easily reach a significant homogeneous nucleation state, and the presence of condensed nuclei such as carbon particles in the exhaust greatly reduces the minimum Gibbs free energy required for volatile vapor nucleation, heterogeneous nucleation is more likely to occur than homogeneous nucleation [53], but the involvement level of each of the three pathways is difficult to study quantitatively and has not been reported, which is a topic for further clarification.

3. Effect of exhaust vapor condensation on fouling and thermal performance

3.1. HC (hydrocarbon) vapor

Table 1 summarizes the results of 37 studies on the effect results of HC condensation on the fouling and thermal performance of EGR coolers. In general, the effects of HC condensation on the fouling are: ① HC condensate increases the total mass of the fouling; ② HC condensate enters the original highly porous fouling, replacing the original gas position and increasing the density of the fouling; ③ HC condensate in the fouling pores makes the fouling fluffy by virtue of the strong capillary force; ④ HC condensate increases the adhesion force on the surface of the fouling, which makes it more difficult to remove the particles deposited on the surface of the fouling, thus increasing the generation rate of the fouling; ⑤ the wet particles formed by HC condensation are more easily deposited on

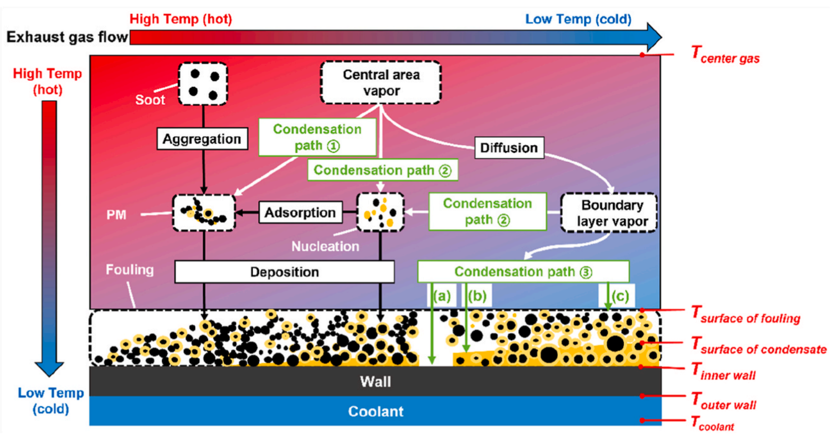

Fig. 2. Diagram of three condensation paths of exhaust vapor in EGR cooler.

Table 1
HC vapor.

Ref	Year	Key control parameter	Key results
Hoard et al. [33]	2008	–	HC condensation forms an adhesive layer on the metal surface and promotes the growth of particle adhesion and fouling.
Sluder et al. [54]	2008	Fuel type: ULSD/B5/B20 Coolant temp.: 90 °C/65 °C/40 °C	B20 fouling has a higher HC fraction than Ultra-low-sulfur diesel (ULSD) and B5 fouling. The mass of fouling and cooler thermal effectiveness degradation is independent of the fuel type. The lower the coolant temperature, the greater the mass of fouling, but the cooler thermal effectiveness loss and pressure drop remain unchanged.
Sluder et al. [55]	2008	Coolant temp. : 85 °C/70 °C/40 °C	The lower the coolant temperature, the greater the mass of fouling and eicosane.
Lance et al. [56]	2009	Fuel type: ULSD/B5/B20	The thermal conductivity of ULSD, B5 and B20 corresponding to fouling was 0.057, 0.034 and 0.032 W/mK, respectively, with an average value of 0.041 W/mK, which was only slightly higher than air and much lower than 304 stainless steel (14.7 W/mK).
Sluder et al. [57]	2009	Fuel type: ULSD/B5/B20 Coolant temp.: 90 °C/65 °C/40 °C	Higher HC concentrations in the feed gas led to higher levels of volatiles in the fouling. Increased HC levels caused an increase in fouling mass, but HC in the fouling did not significantly change the heat transfer characteristics of the fouling at long time scales.
Styles et al. [58]	2010	HC concentration: 35 ppm/250 ppm Coolant temp.: 90 °C/40 °C	The higher the HC concentration, the smaller the thermal performance decay and the greater the mass of fouling; the lower the coolant temperature, the smaller the thermal performance decay and the greater the mass of fouling;
Hong et al. [59]	2011	SOF(n-dodecane) injection rates: No (dry soot)/0.2 mL h^{-1}/0.4 mL h^{-1} Coolant temp. : 80 °C/60 °C/40 °C	The more SOF, the greater the fouling mass and the percentage decrease in thermal performance, and more significant at low coolant temperatures; the "wet soot" containing SOF is more effective at forming fouling on the metal wall surfaces; the mass of fouling is primarily related to the overall decrease in thermal conductivity of the EGR cooler.
Hong et al. [60] and Lee et al. [61]	2011	SOF types: N-dodecane/lube oil Injection rates: No (dry soot)/0.2 mL h^{-1}/0.4 mL h^{-1}	"Wet soot" could be more effective in capturing the particles passing through it, and lubricating oil can contribute more to the mass increase of the fouling than n-dodecane. The condensation of the lubricant could fill the holes in the fouling and reduce the overall thermal resistance to improve the cooler's thermal performance.
Bika et al. [47]	2012	Coolant temp. : 25 °C/30 °C/35 °C/40 °C/45 °C/50 °C HC concentration: 100 ppm/150 ppm/200 ppm/250 ppm Filter smoke number (FSN): 1.0/0.35	Due to the thermophoretic effect, the soot deposition rate increases with decreasing coolant temperature; under the regular operation of diesel EGR cooler, diffusion of HC does not affect the soot deposition rate; under the low FSN condition, nucleated particulate matter increases with increasing HC concentration and decreasing coolant temperature, and when FSN increases, nucleated particulate disappears; therefore, nucleated particulate in EGR cooler is not only related to saturation ratio but also related to FSN.
Warey et al. [41]	2012	HC type: C15/C17/C19/C20/C22/C24	C15 hardly condenses; due to the increased surface temperature of the condensate, which gradually approaches the dew point temperature, the C17–C22 condensate mass reaches the asymptote in 0–1.5 h, while C24 reaches the asymptote after 3 h.
Bravo et al. [62]	2013	HC concentration: 60 ppm/200 ppm/500 ppm	The higher the HC concentration, the higher the fouling thermal resistance, the lower the thermal efficiency and the higher the pressure drop. Compared with the experimental bench sample, the fouling of the onboard EGR cooler fouling has a large amount of HC and oxygen-containing functional groups as well as a small mass of PAHs, resulting in a lower specific surface area.
Bravo et al. [63]	2013	HC concentration: 60 ppm/500 ppm	The fouling at 60 ppm HC is thin, and the fouling at 500 ppm HC is more and thicker and fluffy.
Lance et al. [64]	2013	HC concentration: high/low	High HC fouling has a dense HC layer on the metal and an HC gradient.
Prabhakar et al. [65]	2013	Medium load (2150 rpm, 203 Nm)/low load (1400 rpm, 81 Nm); Coolant temp. : 85 °C/40 °C	Under low load conditions, the fouling volume is larger, mainly due to greater HC condensation and larger pore diameter, but less pore number. The fouling mass is bigger at low cooling water temperatures, with more HC content, more aromatic hydrocarbons, less thermal efficiency loss, and more particulate matter.
Storey et al. [66]	2013	HC concentration: High (100 ppm)/low (50 ppm)	High HC levels initially lead to greater mass and density of fouling, but in subsequent times, the mass and density of fouling are similar to low HC levels. The low HC fouling is divided into a thicker, dense bottom layer and a thin dendritic top layer.
Kuhara et al. [67]	2014	Engine operating condition: Hot start/cold start	The fouling under hot-start conditions has many dimples and more voids; the fouling under cold-start conditions has lower porosity, is a dense layer, and has a higher SOF content. Cold start can recover the thermal properties and reduce the mass of fouling.
Salvi et al. [68]	2014	With/without 24 h bake	After baking, the thickness of the fouling decreases due to HC volatilization, and the thermal conductivity decreases.
Sluder et al. [12]	2014	HC concentration: 50 ppm/100 ppm	In the early stages of fouling formation, the HC condensate film acts as a "glue" increasing the likelihood that particles will adhere to the metal walls.
Paz et al. [69]	2016	HC concentration: 0 ppm/15 ppm	The higher the HC concentration, the higher the percentage of organic carbon in the fouling, and the wetter the fouling.
Kotaro et al. [70]	2016	Cooler wall heating temp.: Room temp./80 °C/90 °C/100 °C/120 °C	High temperature lacquers at high temperatures contain C═O double bonds, and low temperature lacquers at low temperatures contain aromatic hydrocarbons. HC and water may be responsible for the initial formation of the lacquer.
Yoo et al. [71]	2017	Coolant temp. : 65 °C/85 °C	The lower the temperature, the greater the mass of fouling, and the lower the cooler effectiveness, but the pressure drop does not increase.

(continued on next page)

Table 1 (*continued*)

Ref	Year	Key control parameter	Key results
Bravo et al. [72]	2018	Operating conditions: Reference/High HC/High Soot/High HC + Soot Coolant temp. : 40 °C/80 °C	The High HC and High HC + Soot cases have a high thermal performance degradation of the cooler with a pressure drop approximately twice as high as the other conditions, with the highest pressure drop in the High HC + Soot condition.
Lance et al. [73]	2018	Coolant temp. : 85 °C/92.5 °C/100 °C HC concentration: 25 ppm/50 ppm/75 ppm	The lower the temperature near the EGR cooler outlet, the lower the HC condensation, the denser the fouling and the fewer the voids. The higher density of HC-rich fouling due to better thermal conductivity will allow the thermophoretic deposition to further increase the thickness of the fouling. However, an increase in the ratio of soot to HC concentration will cause the fouling to become porous, leading to a plateau of growth and ultimately the formation of thinner fouling.
Park et al. [74]	2018	Coolant temp.: 80 °C/60 °C/40 °C	The lower the coolant temperature, the more severe the cooler thermal effectiveness drop.
Sakaida et al. [75]	2019	HC concentration: 7800 ppm/5900 ppm/4400 ppm	Hard fouling is formed by polycyclic aromatic hydrocarbons (PAHs), and the PAHs in the exhaust gas strongly influence hard fouling.
Paz et al. [43]	2019	$C_{16}H_{34}$ injection flow: No/100 μL/min; Coolant temp. : 90 °C/60 °C/30 °C	$C_{16}H_{34}$ condensation enhances the cooler's thermal efficiency, and the fouling's thickness decreases, mainly acting at low temperatures. There is a strong relationship between the coolant temperature and the thickness of the fouling.
Paz et al. [50]	2019	HC types: $C_{12}H_{26}$/$C_{15}H_{32}$/$C_{16}H_{34}$/$C_{20}H_{42}$	As the fouling layer grows, the surface temperature increases and HC condensation decreases; $C_{12}H_{26}$ is not condensed, $C_{15}H_{32}$ and $C_{16}H_{34}$ are mainly condensed at the low temperature of the cooler outlet, $C_{20}H_{42}$ condensate is the most, and the thickness of fouling caused by $C_{20}H_{42}$ condensate can be up to 1.5%.
Razmavar and Malayeri [44]	2019	With/without 1000 ml/h icosane	Icosane vapor condensation helps remove fouling, reducing fouling resistance and improving cooler effectiveness.
Tanaka et al. [76]	2020	HC concentration: 8483 ppm/8817 ppm/8771 ppm/8684 ppm	PAHs with carbon atom numbers greater than 20 play an important role in hard fouling; PAHs diffuse, adsorb and condense in powdery fouling and eventually form hard fouling.
Williams et al. [11]	2020	Fuel type: B7/Gas Transfer Liquid (GTL)	Compared to B7 (representing European EN590 diesel), Fischer-Tropsch GTL formed 72% less fouling mass.
Paz et al. [45]	2021	HC concentration: 578 ppm/851 ppm/1265 ppm	In the early stage of fouling formation, HC condensation increases the density of fouling and reduces the thickness of fouling; however, as the fouling grows, HC condensation stops, and the density of fouling becomes smaller and approaches the density when there is no condensation.
Zhang et al. [77]	2021	Coolant temp. : 65 °C/75 °C/85 °C	The lower the coolant temperature, the more HC condensation, the greater the mass of fouling, and the lower the cooling effectiveness per unit tube length.
Li et al. [51]	2022	HC concentration: 200 ppm/450 ppm/850 ppm	The promotion effect of HC condensation on particle deposition can only be in a specific range, and too high HC concentration is not conducive to particle deposition. At low HC concentration, the fouling is divided into a thin, loose flocculent dendritic layer and a thick, dense layer; at high HC concentration, the fouling is densely layered with flocculent particle clusters scattered on the surface; at very high HC concentration, HC volatilization leads to a rough fouling structure and reduced density.
Liebsch et al. [78]	2022	HC concentration: basis/+50%/+100%/-50%	The higher the HC concentration, the greater the mass of fouling.
Williams et al. [79]	2022	Fuel type: B7/GTL; With/without additives	Paraffinic diesel fuel (GTL) produces less fouling than B7 diesel; the mass of fouling is weakly correlated with HC concentration; effective additives can reduce the mass of fouling.
Han et al. [46]	2023	HC concentration: 411 ppm/590 ppm/754 ppm	The higher the HC concentration, the larger the fouling mass, the more yellow the color, the stronger the hydrophilicity, and the denser the micromorphology. Above 160 °C, HC condensation is largely inhibited. The HC and soot heat transfer skeleton together determines the cooler's thermal performance.

the inner wall of the EGR cooler; ⑥ the nucleation of HC condensate can generate nucleated and aggregated particles; ⑦ The flow of HC condensate can remove some of the fouling; ⑧ HC condensate makes the interface between the fouling and the metal wall of the cooler more tightly bound and more difficult to be removed, which is the result of the polymerization and reaction of the HC condensate and the stronger bonding of the generated products with the metal wall surface. The vast majority of the results are consistent with the above summary; only the study by Bika et al. showed that the condensation diffusion of HC did not affect the deposition rate of particulate matter [47], which may be related to the fact that condensation nucleation complemented the deposited particulate matter.

Although there is a high degree of consensus on the effect results of HC condensation on fouling, but a significant disagreement on the effect results of HC condensation on the thermal performance of EGR cooler. A part of studies indicate that HC condensation can improve the thermal performance of the cooler, representative of the literature [43,44,46,65]; on the contrary, another part of studies indicate that HC condensation deteriorates the heat transfer performance of the cooler, representative of the literature [59,67,77], and the last part of studies indicate that HC condensation has little effect on the thermal performance of the cooler [54,57].

To clarify the root of this disagreement, the effect results of HC condensation on fouling needs to be further analyzed in term of heat transfer, and effects can be divided into two aspects, beneficial and harmful.

The first type of result is beneficial for thermal performance. As mentioned earlier, HC condensation has eight effects results on fouling, among which, the root cause of ①, ②, and ③ can be attributed to the fact that HC condensation plays the role of filler, which is a physical effect that replaces the pores originally filled with exhaust gas in fouling and increases the overall density and mass of fouling, while the intervention of liquid phase force intervenes to change the originally fluffy fouling into a compact state, which further enhances the density of the fouling and reduces the thickness of the fouling. Therefore, the transformation of the fouling's mass, density, and thickness can improve the cooler's heat transfer performance. The removal effect in which ⑦ makes the fouling decrease, which is closer to the clean state of the cooler and obviously can improve the cooler's thermal performance. The chemical effect of which ⑧ changes the components of fouling, and although the specific components vary depending on the boundary conditions, the product after the polymerization reaction has a larger molecular weight, is a very dense lacquer-like type of fouling, has a greater bond with the metal wall surface, and is significantly different from the fluffy dendritic part of the top layer of fouling [62,70,80]; therefore, the chemical effect facilitates the heat transfer.

The second type of result is harmful to thermal performance. The underlying cause of ④ and ⑤ is that the condensed HC changes the adhesion of the particles and fouling, which both makes the particles easier to bind and deposit during the evolution of collision, polymerization, etc., and makes the deposited particles more difficult to remove. Hence, the condensed HC shows the adhesion effect in this process, which makes the generation of more fouling and leads to the degradation of the thermal performance of the cooler. The nucleation effect in which ⑥ makes more particles generated, and particles are an important source of fouling formation; therefore, the nucleation effect will also indirectly increase the generation of fouling and reduce the cooler thermal performance.

To sum up, the filling effect, removal effect, and chemical effect of HC condensation are beneficial to promote heat transfer, while the adhesion effect and nucleation effect are harmful to deteriorate heat transfer, and finally, the thermal performance of the cooler is the combined result of the beneficial and harmful effects. In the first-party study, the beneficial effect induced by HC condensation is greater than the harmful effect, and therefore, the overall performance of the cooler is improved; while in the second-party study, the harmful effect induced by HC condensation is greater than the beneficial effect, and therefore, the overall performance of the cooler is decreased; while in the third-party study, the harmful effect caused by HC condensation was approximately equal to the beneficial

Table 2
Water vapor.

Ref	Year	Key control parameter	Key results
Teng et al. [81]	2010	With/without a high relative humidity environment	Soot hydration leads to a significant refreshment effect, which makes the cooler effectiveness close to the beginning of the fouling test.
Abd-Elhady et al. [82]	2011	With/without 1.0 l/h water in the exhaust gas	Water vapor condensation can improve the cooler's thermal performance and reduce thermal resistance, but this effect decreases with increasing airflow velocity.
Tomohiko et al. [83]	2011	Exhaust gas inlet - outlet temperature: 270-200 °C/230-160 °C/190-120 °C	With the same temperature difference between the inlet and outlet exhaust gases, the temperature range is lower, and the mass of fouling is greater under the condition of generating condensate; compared with the absence of condensate, the fouling generated under the condition of having condensate is easier to be removed after drying.
Abarham et al. [84]	2012	Coolant temp. : 80 °C/20 °C	Water vapor condensation can relax the fouling at the interface between the fouling and the metal wall surface, causing it to crack and fall under the shear action of the airflow.
VÖLK et al. [85]	2012	Coolant temp. : 80 °C/60 °C/40 °C/20 °C	Condensation of water vapor can cause fouling to become brittle and fall off.
Warey et al. [42]	2013	Coolant temp. : 100 °C/50 °C/25 °C	Water vapor condensation can significantly reduce the mass of fouling composed of dry soot and can be used as a periodic cleaning regeneration method. Still, it has little effect on removing fouling containing condensed HC.
Furuhata et al. [86]	2014	Coolant temp. : 80 °C/40 °C	The effect of cooling water temperature on the thickness of the fouling was not significant. Water vapor condensation may have caused the fouling layer to peel off, making the thickness smaller and more significant in the case of intermittent exhaust gas flow.
Koji et al. [87]	2014	Coolant temp. : 80 °C/15 °C	Water vapor condenses between the fouling and the metal wall or inside the fouling, and this expansion causes the fouling to peel off, reducing the thickness of the fouling.
Warey et al. [88]	2014	Coolant temp. : 50 °C/25 °C	Water vapor condensation, combined with a pre-EGR cooler oxidation catalyst, can remove about 90% fouling mass.
Kotaro et al. [70]	2016	Cooler wall heating temp.: Room temp./ 80 °C/90 °C/100 °C/120 °C	The condensed water is helpful in the formation of high-temperature lacquer-like fouling.
Konno et al. [89]	2017	With/without condensate water in fouling	The repeated generation and drying of condensate accelerate the growth of resinous hard fouling, mass greater.
Norimitsu et al. [90]	2017	Coolant temp. : 80 °C/35 °C	Water vapor condensation is useful for fouling removal, reducing the thickness of the fouling, which can restore the thermal effectiveness, and the removal effect increases with the increase of airflow velocity; the location of condensate generation is related to the thickness of the fouling.
Seungchul et al. [91]	2017	With/without 10g detergent (water + methanol) in the exhaust gas	Containing water detergent reduces the fouling factor and improves the heat exchange effectiveness, restoring the thermal performance of the EGR cooler almost to a clean state.
Itoh et al. [92]	2019	Cooler wall temp.: 94 °C/99 °C/100 °C	The condensate produced by the cold start separates the fouling from the wall, but the higher the temperature of the cooler wall, the more difficult it is to separate; the condensate makes the fouling containing diesel easier to separate.
Razmavar and Malayeri [44]	2019	With/without 1000 ml h^{-1} water in the exhaust gas	Water vapor condensation helps to remove some of the fouling, which reduces fouling resistance and improves effectiveness.

effect, and therefore, the overall performance of the cooler remained unchanged.

However, it is difficult to quantify the contribution degree of each of the five effects of HC condensation, and the contribution degree of each effect to heat transfer depends on the boundary conditions. In addition, the cooler thermal performance is affected with different response rates by the five effects; in comparison, where the filling effect on thermal performance is fast, the removal effect is instantaneous, and the chemical, adhesion, and nucleation effects take longer to become significant, they are slow. Therefore, on a time scale, if the change in the thermal performance of the cooler due to HC condensation is tested over a short period, it usually shows an improvement in the heat transfer performance of the cooler due to the filling effect, while if the experimental results are observed over a longer time scale, it usually shows a decrease in the thermal performance of the cooler due to the long-lasting effects of the adhesion and nucleation effects.

3.2. Water vapor

Table 2 summarizes the effects of water vapor condensation on EGR cooler fouling and thermal performance. In general, the effect results of water vapor condensation on fouling are: ① water vapor condensate increases the overall mass of fouling; ② due to the hydrophobic nature of dry carbon soot, condensate promotes the separation of fouling from the inner wall, and the mass of fouling decreases; ③ due to the hydrophobic nature of dry carbon soot, condensate promotes the separation of fouling from the inner wall, and the thickness of fouling decreases; ④ condensate promotes the generation of high-temperature lacquer fouling, and the mass is greater. It is easy to see that the condensation of water vapor shows different results in different studies, which is difficult to unify; in fact, these results focus on describing different stages, ④ more emphasis on the role played by condensate in the initial stage of fouling formation, the condensate liquid film as a substrate bed absorbed a large number of HC with polar groups, and then the water evaporated at high temperature, and the polymerization reaction occurred between different HC, which accelerated the formation of hard high temperature fouling formation; ① focuses on describing the establishment process before condensate removes fouling, this process, condensate is increasing, but still not enough to remove fouling, therefore, the overall mass is increased; ③ and ④ focus on describing the result after condensate removes fouling, the mass of fouling in the cooler will decrease once the condensate accumulates to a certain amount that is sufficient to embrittle and dislodge the fouling and discharge it from the cooler. Therefore, the effect of water vapor condensation on fouling at different stages is different.

Interestingly, the effect results of water vapor condensation on the thermal performance of the cooler are highly consistent, with all studies showing that water vapor condensation is beneficial for the thermal performance of the cooler. To fundamentally understand why water vapor condensation has a significant heat transfer-enhancing effect, we still dissect it from the heat transfer perspective. Among the four effect results of water vapor condensation on fouling, ① is the result of the filling effect, ② and ③ is the result of the removal effect, ④ is the result of the adhesion effect; among them, the filling effect and the removal effect of condensate are beneficial effects of improving heat transfer, while the adhesion effect contributes to the generation of hard lacquer fouling, which is a harmful effect for the heat transfer performance of the cooler, but because of the thermal conductivity of hard lacquer fouling is relatively high, the influence of the adhesion effect on the thermal performance of the cooler is very limited. The real decisive effect is still the filling effect and the removal effect, especially the removal effect; once the fouling is removed, the thermal performance of the EGR cooler will be close to the thermal performance in a clean state. In summary, the results of the effect of water vapor condensation on the thermal performance of the EGR cooler are all shown to be beneficial to heat transfer.

3.3. Acid vapor

Table 3 summarizes the effect results of four acid vapor condensations on fouling and EGR cooler performance. In general, the effect results of vapor condensation from the combustion of sulfur-containing components in the fuel on fouling are: ① increasing the number of particles in the exhaust gas that are nucleated in heterogeneous phase; ② increasing the rate of particle deposition; ③ increasing the content of sulfate in fouling, such as iron sulfate; and ④ increasing the mass of fouling. Where ① and ② are the results of the nucleation effect, ③ is the result of the sulfuric acid condensate and EGR cooler metal wall reaction product, which results from the chemical effect, and ④ is the result of the filling effect.

As global emissions regulations advance and sulfur content in fuels continues to decrease, the effect of sulfate vapor condensation on fouling and cooler performance is not a hot topic of research today, and no publications describe the relationship between acid

Table 3
Acid vapor.

Ref	Year	Key control parameter	Key results
Girard et al. [93]	1999	Sulfur concentration: 370 ppm/4000 ppm	Sulfate in fouling is derived from particle-related sulfate in the exhaust gas; increasing the sulfur content of the fuel increases the amount of particulate matter, especially ultrafine particles (<50 nm diameter), as a result of heterogeneous nucleation of H_2O and SO_3.
Usui et al. [94]	2004	Sulfur concentration: 350 ppm/50 ppm/10 ppm	Thermophoretic force and Stefan flow are responsible and dominant mechanisms of diesel exhaust particulate deposition onto a cooling plate. The higher the sulfur concentration, the higher the deposition velocity.
Lance et al. [95]	2010	–	Sulfate is present in fouling, and the metal matrix has a hydrated iron sulfate with a 2–3 μm thickness.
Sturm et al. [96]	2012	Sulfur concentration: 1000 ppm/5 ppm	Fouling can be divided into three states according to the exhaust gas temperature: ① controlled dry fouling; ② fouling with severe contamination or even leading to clogging; ③ fouling can be flushed by condensate; the larger the sulfur concentration, the larger the mass of fouling and the pressure drop of EGR cooler.

vapor and EGR cooler thermal performance. However, as with HC vapor and water vapor condensation, the nucleation effect of acid vapor condensation leads to more fouling, which is harmful to the thermal performance of the EGR cooler, while the chemical effect leads to the production of high thermal conductivity sulfates, which is beneficial for the thermal performance of the EGR cooler, and the filling effect is also beneficial for the thermal performance of the EGR cooler by reducing the overall porosity of the fouling.

3.4. Comparison of different vapors

Table 4 highlights the results of four studies comparing EGR cooler fouling and thermal performance with different vapor and mixed vapor condensation. The results collectively show that: ① water vapor has the highest condensation flux compared to HC and acid vapor; ② whatever vapor, condensation diffusion both lead to high deposition efficiency; ③ both HC and water vapor condensation can recover the cooler thermal efficiency; ④ HC and water vapor condense at the same time with the least fouling; ⑤ most of the results indicate that the thermal efficiency recovery with water vapor condensation is the result of fouling removal, while Bika et al. suggested that the efficiency recovery was not due to the removal of fouling by condensate, but rather the change in the morphology of fouling by condensate [97].

3.5. Five effects

Based on the above analysis, it can be seen that whether it is HC vapor, water vapor, or acid vapor, the effect of their condensation on the fouling and thermal performance of the EGR cooler is achieved through three paths and five effects, as shown in Fig. 3, the combined effect of these five effects through exhaust vapor condensation changes the heat transfer properties of the fouling such as component, mass, thickness, and density. These parameters directly determine the ②$\boldsymbol{R_{cond\text{-}fouling}}$ in Figs. 1 and 3 and ultimately lead to changes in the thermal performance of the EGR cooler.

Three of the five effects are beneficial for the thermal performance, including the filling effect, removal effect, and chemical effect, which are marked with green font and ↑in Fig. 3; at the same time, two effects are harmful to the thermal performance, including the adhesion effect and nucleation effect, which are marked with red font and ↓in Fig. 3. When the vapor condensate enters the fouling, the filling effect which is beneficial for the thermal performance and the adhesion effect which is harmful to the thermal performance exist simultaneously, and these two effects are in a competitive relationship. The thermal performance of the EGR cooler may be either increased or decreased and unchanged. In the real engine exhaust environment, all five effects may exist simultaneously, and the competing relationship between multiple beneficial and harmful effects analyzes EGR cooler thermal performance more difficult.

3.6. Control and prevention of exhaust gas vapor condensation

Among the typical vapor condensation in EGR coolers, the use of water vapor condensation has been shown in several studies to form a useful strategy for periodic cleaning of EGR cooler fouling due to its effectiveness in significantly removing fouling and recovering the thermal performance of EGR coolers [66,81,84,86,88]; At the same time, global emission regulations have seen several iterations over the past 25 years, and the significant reduction of sulfur content in fuels has allowed for effective control of acid vapor condensation on EGR cooler corrosion and fouling, which is no longer a major form of EGR cooler failure. Unlike water vapor and acid vapor, although some studies have found that HC vapor condensation can modify fouling to improve the thermal performance of EGR coolers, several studies have shown that HC vapor condensation can lead to significant degradation of EGR cooler thermal performance and the highest pressure drop, or even complete blockage in long time dimensions [11–13,99]; thus HC condensation is the main form of failure.

To combat HC vapor condensation-induced failure, several useful studies have found that catalytic devices (e.g., Diesel Oxidation Catalyst (DOC)) installed upstream of the EGR cooler can significantly reduce the HC concentration in the exhaust gas and thus reduce fouling to improve the thermal performance and long-term stability of the EGR cooler; however, this approach typically introduces a significant pressure drop and higher cost [33,55,74,88,100]. What's more, using non-thermal plasma (NTP) technology injects plasma

Table 4
Comparison of different vapors.

Ref	Year	Key control parameter	Key results
Hörnig et al. [98]	2011	Dry soot/soot + H_2O/soot + HC/soot + H_2O + HC/soot + H_2O + HC + H_2SO_4	Condensation triggered by low coolant temperature and low gas temperature makes diffusion swimming work and leads to high deposition efficiency of particles; to improve the thermal performance of EGR coolers, wash-out effects from H_2O condensation should be induced, and scenarios without condensate but with large amounts of condensed HC should be avoided.
Abarham et al. [48]	2012	H_2O/docosane/Sulfuric acid/Nitric acid	Compared to other condensates, water condensation fluxes dominate; docosane does not condense above 80 °C, and lighter HCs even less so. Water vapor diffuses through the porous fouling to the colder metal walls, weakening the van der Waals forces between the fouling and the metal walls and lifting the fouling, contributing to the removal effect.
Bika et al. [97]	2013	Exposure condition: Dry/HC + H_2O/H_2O	Dry makes the effectiveness recovery less than 20%, and condensation under both HC + H_2O and H_2O conditions can make the effectiveness recovery more than 80% due to the condensate changing the morphology of the fouling rather than removing the fouling.
Razmavar and Malayeri [44]	2019	Exposure condition: 1000 ml/h H_2O/icosane/H_2O + icosane	Icosane condensation improves the effect by 15% more than water condensation; when icosane and water vapor are condensed simultaneously, the amount of fouling is the least, which is the main effect of fouling removal.

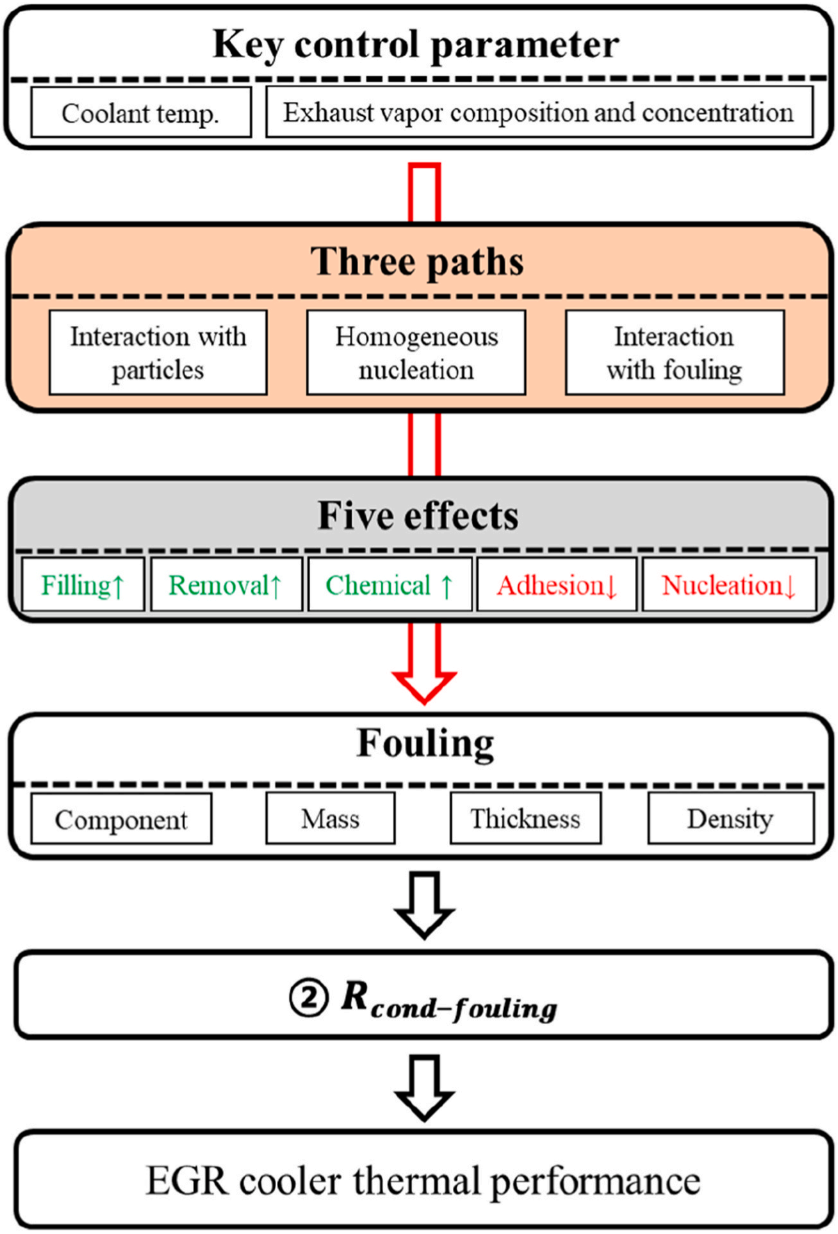

Fig. 3. Five effects of exhaust vapor condensation on EGR cooler fouling and thermal performance.

into the interior of the EGR cooler to remove HC by reacting the plasma with the HC in the fouling to reduce the adhesion effect and achieve fouling removal. This technique also reduces the potential risk of HC vapor condensation. Still, it requires the installation of an additional plasma injection unit, which inevitably adds some maintenance costs [101–103]. Since this technique has not been applied in real vehicles, the effect of the products of the reaction between plasma and HC on engine combustion has not been confirmed.

3.7. Challenges and prospects

From 1998 to 2023, a logical chain of relationships has become clear as the study of the effects of exhaust gas vapor condensation on EGR cooler fouling and thermal performance has yielded rich results and significant advances. However, some challenges remain to be addressed.

First, quantifying the involvement of vapor condensation sub-paths and the level of contribution of sub-effects is the larger challenge. Although this review clarifies the existence of both beneficial and harmful effects of vapor condensation on thermal performance from a macroscopic perspective and explains the controversial results of past studies, since beneficial and harmful usually go hand in hand, the thermal performance of a cooler only shows the combined result of the two offsetting effects. To truly understand the extent of the effect of vapor condensation mechanistically, it is necessary to separately quantify the extent of the contribution of beneficial and harmful, but none of the past studies investigated this point; similarly, the quantitative description of the condensation sub-path has not been investigated, so future studies can be conducted from these two sub-topics to more thoroughly elucidate the process of exhaust gas condensation in EGR coolers and its effect on fouling and thermal performance.

Second, establishing a standard database (including exhaust gas input conditions, fouling, and thermal performance results) is another challenge. Whether it is HC vapor, water vapor, or acid vapor condensation, we can see from Tables 1–3 that the distribution of key control parameters varies greatly from study to study, making it difficult to make quantitative cross-sectional comparisons between studies. Although the input conditions (temperature, components, concentration, etc.) of the exhaust gases vary significantly with engine type (gasoline or diesel), operating conditions, and EGR cooler type, the overly variable input conditions also make the results highly discrete. Therefore, we suggest that in the future, researchers can study fouling and thermal performance data under typical system control parameters from the perspective of building a standard database.

Third, it is still more challenging to construct models that include both fouling generation and thermal performance prediction in EGR coolers. In the past, there are models describing particle deposition, vapor condensation, fouling growth mass or thickness, and thermal performance and pressure drop of EGR coolers, but these models are only oriented to a certain object or a certain characteristic parameter, and lack models that systematically describe the "vapor condensation-fouling-thermal performance" transfer relationship, which is a research direction that can be further developed in the future.

Fourth, the effect of renewable synthetic fuels on EGR cooler fouling and thermal performance needs to be further investigated. With the advancement of global emission regulations and the requirement of carbon neutrality, renewable synthetic fuels synthesized from hydrogen and carbon dioxide using green electricity such as wind or solar power are one of the highly promising fuels of the future. However, the emission characteristics of such new fuels after combustion may differ from those of conventional fuels due to the different compositions, and therefore, the condensation of exhaust gases in the EGR cooler also differs, which in turn leads to fouling and thermal performance that differs from the results of past studies. To reasonably assess the suitability of renewable synthetic fuels and EGR coolers, studies on the effects of such fuels on the fouling and thermal performance of EGR coolers need to be conducted.

4. Conclusion

Exhaust gases from engine combustion inevitably contain particulate matter, HC vapor, water vapor and so on, which will form fouling in the EGR cooler under the complex action of flow and thermal fields, which may lead to cooler failure and thus high levels of NOx emissions. To clarify the relationship between exhaust vapor condensation, fouling and thermal performance, this paper compiles the results of studies from 1998 to 2023, summarizing their consensus and disagreement, as well as the root causes of the disagreement, and proposing three pathways and five effects of exhaust gas condensation, which are useful not only for understanding the mechanism of fouling in EGR coolers from a new perspective but also have important implications for the anti-fouling design of compact heat exchanger or cooler which used to cool multiphase streams containing particulate matter. In general, the following points were concluded.

1. Vapor condensation in EGR coolers has three pathways: interaction with particles (surface condensation and heterogeneous nucleation of particles), homogeneous nucleation of the vapor itself, and interaction with the fouling.
2. Exhaust vapor condensation affects the composition, mass, thickness, densification, and morphology of the fouling through five effects, including adhesion, nucleation, filling, removal, and chemical effects, which in turn change the thermal resistance of the fouling and ultimately affect the thermal performance of the EGR cooler.
3. HC vapor condensation can either enhance the thermal performance of the EGR cooler, reduce the thermal performance of the cooler, or have no effect on the thermal performance, which is the combined result of multiple effects competing with each other, and water vapor condensation can enhance the thermal performance of the cooler.
4. The rational application of water vapor condensation can be used to restore the thermal performance of the EGR cooler. In contrast, the condensation of HC should be prevented as much as possible, and there are currently two solutions for retrofitting catalytic devices and NTP technology.
5. Topics that can be further developed in the future are:
   ① The participation level of each of the three pathways and the contribution degree of each of the five effects of vapor condensation under different boundary conditions.
   ② Construction of a standard database for typical operating conditions.
   ③ Construct a holistic model that includes vapor condensation, fouling, and thermal performance.
   ④ Effect of renewable synthetic fuels on EGR cooler fouling and thermal performance.

CRediT author statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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