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Review of thermal management of catalytic converters to decrease engine emissions during cold start and warm up

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HIGHLIGHTS

- Thermal management methods of catalytic converters were analyzed in detail.
- Methods based on the control of engine parameters bring significant fuel penalty.
- Extra heating devices allow flexibility of heat injection.

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ABSTRACT

Catalytic converters mitigate carbon monoxide, hydrocarbon, nitrogen oxides and particulate matter emissions from internal combustion engines, and allow meeting the increasingly stringent emission regulations. However, catalytic converters experience light-off issues during cold start and warm up. This paper reviews the literature on the thermal management of catalysts, which aims to significantly reduce the light-off time and emission concentrations through appropriate heating methods. In particular, methods based on the control of engine parameters are easily implementable, as they do not require extra heating devices. They present good performance in terms of catalyst light-off time reduction, but bring high fuel penalties, caused by the heat loss and unburnt fuel. Other thermal management methods, such as those based on burners, reformers and electrically heated catalysts, involve the installation of additional devices, but allow flexibility in the location and intensity of the heat injection, which can effectively reduce the heat loss in the tailpipe. Heat storage materials decrease catalyst light-off time, emission concentrations and fuel consumption, but they are not effective if the engine remains switched off for long periods of time. The main recommendation of this survey is that integrated and more advanced thermal management control strategies should be developed to reduce light-off time without significant energy penalty.

1. Introduction

Internal combustion (IC) engines for vehicle propulsion are facing major challenges due to their relatively high emissions and low efficiency. Nevertheless, mainstream projections indicate that IC engines will still be widely used for a relatively long period [1], at least as parts of hybrid electric powertrains. Hence, the automotive industry is making significant efforts to further reduce IC engine emissions, i.e., carbon monoxide (CO), hydrocarbon (HC), nitrogen oxides (NO_x) and particulate matters (PM) [2]. To this purpose, after-treatment systems, such as three-way catalysts (TWCs) [3], diesel oxidation catalysts (DOCs) [4], selective catalytic reduction (SCR) systems [5] and diesel particulate matter filters (DPFs) [6], have been successfully implemented in spark ignition (SI) and compression ignition (CI) engines. However, as most of the after-treatment systems are catalytic converters, their functionality deteriorates at low temperature, e.g., during engine cold start and warm up [7]. In fact, catalysts usually convert harmful emissions only when their temperature reaches certain thresholds, i.e., the so-called light-off temperature, which is normally around 250–300 °C for TWCs [8]. Hence, high levels of exhaust emissions are transferred into the atmosphere while the exhaust temperature is low, during the engine cold start or warm up phases, in which the catalyst is not fully operational [9]. For example, during a new European driving cycle (NEDC) from cold conditions, with a total duration of ∼1200 s, the exhaust temperature is typically below the catalyst light-off level for over 200 s [10]. Up to 80% of CO and HC are emitted during this period, which is less than 20% of the total duration of the cycle [11]. In addition, during cold start, a considerable amount

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Nomenclature

Abbreviations

CA	crank angle
CI	compression ignition
CO	carbon monoxide
CO_2	carbon dioxide
CCR-DPF	catalysed continuously regenerating diesel particulate filter
CR-DPF	continuously regenerating diesel particulate filter
CSF	catalyst soot filter
DOC	diesel oxidation catalyst
DPF	diesel particulate fliter
EHC	electrically heated catalyst
EVO	early exhaust valve open
FBC	fuel borne catalyst
FMEP	friction mean effective pressure
FTP	federal test procedure
GDI	gasoline direct injection
HC	hydrocarbon
HEVs	hybrid electric vehicles
IC	internal combustion
IVO	intake valve opening
NEDC	new European driving cycle
NH_3	ammonia gas
NO	nitric oxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxide
PM	particulate matter
POX	partial oxidation
SCR	selective catalytic reduction
SI	spark ignition
SOI	start of injection
SOF	soluble organic fraction
TWC	three way catalyst
ULEV	ultra-low emission vehicle
VGT	variable geometry turbine
VNT	variable nozzle turbine
VVT	variable valve timing
λ	equivalent ratio

of gas-phase HC condenses on the surface of the tailpipe and catalyst, and partially volatilises to the atmosphere without catalytic oxidation during the following warm up phase [11]. Also the DPFs have regeneration issues in conditions of low exhaust temperature. In fact, to maintain DPF performance, periodical or continuous DPF regeneration is needed to remove the particles accumulated on the filter. In particular, catalyst soot filters (CSFs) [12], fuel borne catalysts (FBCs) [13], continuously regenerating diesel particulate matter filters (CR-DPFs) [14] and catalysed continuously regenerating diesel particulate filters (CCR-DPFs) [15] show excellent regeneration characteristics only at temperatures higher than 350 °C.

The thermal management of catalytic converters is a timely topic. In fact, in the current context of the automotive sector, hybrid electric vehicles (HEVs) play an increasingly important role. HEVs allow IC engines to operate more efficiently, and partially recuperate their kinetic energy during braking [16]. However, HEVs still face the challenge of cold start emissions, as HEV engines are usually switched off at low speed and wheel torque, when the brake specific fuel consumption is particularly high. This may reduce the exhaust temperature, and thus the catalyst efficiency. Therefore, the thermal management of the catalyst is important for both conventional vehicles and HEVs.

To add complexity, the interaction between the different types of after-treatment devices has a major influence on the system performance. For example, heat release occurs during the catalytic action of the DOC, which increases the exhaust temperature. As the DPF regeneration temperature is much higher than the DOC light-off temperature, the heat release in the DOC helps the DPF regeneration, and thus the DPF is often located on the downstream side of the DOC. In production diesel engines, fuel is often injected into the exhaust before the DOC to achieve DPF regeneration assisted by the heat release of the DOC catalytic actions [17]. During the DOC operation, part of the NO is converted into NO_2, which contributes to the DPF regeneration [18] and SCR reaction [19]. The flow through the SCR catalyst also has a reduction effect on the soluble organic fraction (SOF) contained in the PM, hence in some implementations the SCR and catalysed DPF are combined to decrease PM and NO_x emissions [20].

A large amount of research has been undertaken to investigate catalyst characteristics and improve catalyst light-off performance through appropriate thermal management. Nevertheless, the literature misses a detailed survey on the thermal management of catalytic converters to decrease exhaust emissions during engine cold start and warm up. Such gap is covered by this contribution, which reviews the research and development activities on the topic, and includes a critical analysis of the different heating methods.

2. Exhaust emissions of IC engines during cold start and warm up

Ref. [20] provided a detailed review on cold start emissions. Several studies, e.g., Ref. [21] and Ref. [22], report experimentally measured high CO and HC emissions for both gasoline and diesel engines in cold start conditions. In the analysed papers the maximum concentrations of CO and HC ranged from ~950 ppm to ~8400 ppm and from ~220 ppm to ~28,000 ppm, respectively [22–31]. Such high emissions are caused by poor cylinder combustion and catalyst efficiency. The particle number concentration does not significantly vary during cold start, while it is closely related to engine speed and load [32]. Although less elemental carbon forms in cold start conditions due to the low cylinder temperature, much more gas-phase HC converts into liquid-phase particles. Hence, the drop of HC concentration contributes to PM decrease in cold start conditions. Ref. [33] also observed high NO_x emissions, mainly caused by low catalyst efficiency. In particular vehicles, such as the airport shuttle buses, sightseeing buses and urban buses, the exhaust temperature can be permanently below the catalyst light-off level. In ultra-low emission vehicles (ULEVs) [34], 80–90% of the tailpipe HC emission occurred during the first test cycle in the federal test procedure (FTP) according to Gong et al. [35], and these values can further increase in super ULEVs.

Given these facts, measures were taken or evaluated to reduce emissions during warm up by improving: (i) combustion; and/or (ii) catalyst efficiency. For example, with respect to (i), an appropriate heat storage or additional heat source can increase the lubricant [36] or coolant [37] temperature before the engine starts, and effectively raise the cylinder temperature to reduce CO and HC formation. Also intake air heating [38] and fuel heating [39] can improve combustion. With respect to (ii), the typical methods vary the operational engine parameters, e.g., they adjust the valve timing, enrich the air/fuel mixture and adjust the start of combustion. Such methods can effectively decrease the catalyst light-off time; nevertheless, IC engine emissions remain deteriorated before the catalyst light-off. Hence, to accelerate light-off, a pre-catalyst device could heat the exhaust.

Among the multiple methods to effectively decrease cold start and warm up emissions, this paper mainly reviews those based on the thermal management of the catalytic converters.

3. Catalyst performance during cold start and warm up

TWCs, DOCs, SCR systems and DPFs are successful commercial products that reduce primary exhaust emissions, i.e., CO, HC, NO_x and PM. In particular, TWCs decrease SI engine emissions in conditions of stoichiometric air/fuel ratio. DOCs achieve the oxidation of CO and HC with a 40–60% conversion efficiency, and also contribute to the decrease of PM emissions both in mass and number, as liquid-phase HCs are one of the main components of PM [40]. In DOCs part of the nitric oxide (NO) is oxidized into nitrogen dioxide (NO_2), which contributes to PM oxidation during continuous DPF regeneration, and promotes the NO_x catalytic reaction with ammonia gas (NH_3) in SCRs. Only the DPF implementations including fuel additives and catalyst coating, used in the DPF channels as passive regeneration methods, are considered in this review.

Exhaust temperature plays an important role in catalyst performance. It tends to be rather low in real driving cycles, which causes low catalyst efficiency [41]. Robinson et al. [10] showed the inlet exhaust temperature history of a DOC during NEDCs from cold and hot conditions. During the cold NEDC, the inlet temperature was below 130 °C in the majority of the first 400 s, and temperatures greater than 180 °C were achieved only in a small portion of the hot driving cycle. SCR devices have similar problems, as in Ref. [42] more than 1000 s were required to reach the SCR light-off temperature.

Catalyst performance during cold start and warm up differs with fuel, which influences the cylinder combustion and exhaust temperature. The exhaust temperature for SI engines is much higher than that of CI engines, which causes shorter TWC light-off time in cold start conditions. For example, in Ref. [21] it took less than 100 s for the exhaust temperature to reach 200 °C for a four stroke SI engine. Blending gasoline with ethanol increases the oxygen content, which causes higher exhaust temperature, as well as high specific fuel consumption due to the low heating value of ethanol [30]. The viscosity of biodiesel, i.e., a blend of diesel and soybean-oil, is higher than that of common diesel. This brings disadvantages in terms of poor air/fuel mixture formation, with a consequent catalyst light-off delay, though biodiesel has high oxygen content [43]. In hydrogen enriched compressed natural gas (HCNG) engines, the hydrogen promotes combustion with high flame propagation velocity [44], which brings faster catalyst light-off with respect to compressed natural gas (CNG).

4. Overview of thermal management methods to reduce cold start and warm up emissions

The high emissions during cold start and warm up primarily depend on low in-cylinder and exhaust temperatures, and thus effective thermal management of the catalytic converter must address these problems [45]. However, very high catalyst temperatures increase the possibility of thermal sintering, and usually imply energy penalties. Therefore, thermal management design is a trade-off among catalyst efficiency, fuel consumption and thermal sintering, and should holistically consider the engine, the heating device (if applicable) and the catalyst.

Various thermal management methods were investigated in the literature. A simple solution is to locate the catalyst closer to the engine; however, after warm up the high exhaust temperature may cause thermal sintering [55], which shortens catalyst lifetime [56] and compromises its performance [57]. Extra combustion devices [58], higher idle speed [59], variable valve timing [47], retarded ignition timing [60], heat storage devices [61] and electrically heated catalysts (EHCs) [62] have been employed to improve light-off performance during warm up.

Table 1 reports examples of results of different thermal management methods from the literature. The light-off time decrease ranged from 20% to 90%, with significant reductions of the maximum emission concentrations.

5. Catalyst heating methods based on IC engine parameters

The adjustment of the operational engine parameters can rather easily achieve high exhaust temperatures in a short time, however it makes the engine deviate from the optimal working conditions. The next subsections critically analyse the effect of such methods.

5.1. Start of combustion delay

5.1.1. Spark ignition engines

Retarded ignition timing is a common and effective method to increase the exhaust temperature without extra devices [63]. However, it reduces the constant volume combustion and leads to more unburned fuel in the exhaust pipe, with subsequent deterioration of engine power and efficiency.

Fig. 1 shows an example of light-off time and fuel consumption characteristics as functions of the retarded ignition timing, expressed with respect to the calibrated engine ignition timing (0 ° CA). The light-off time decreased by 60 s for a retarded ignition timing of 10 ° CA, with a ~10% fuel consumption increase, while the fuel penalty to achieve a catalyst light-off time reduction of 86 s was ~50%. Given its significant fuel penalty, retarded ignition timing should be applied with moderation and combined with other heating measures.

Table 1
Overview of the catalyst performance improvement associated with different thermal management methods.

Thermal management methods	Concentration/ppm or conversion efficiency/%						Light-off time reduction or emission reduction
	Without thermal management			With thermal management			
	CO	HC	NO_x	CO	HC	NO_x	
Start of combustion delay [46]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	~80%[t]
Higher idle speed [35]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	~90%[t]
Variable valve timing [47]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	~30%[a]
Air/fuel ratio adjustment [48]	~45%	n.a.	n.a.	~60%	n.a.	n.a.	n.a.
After-treatment layout [49]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	~26%[t]
Burner [50]	n.a.	n.a.	n.a	n.a.	n.a.	n.a	~40%[t]
Reformer [51]	~5500[c]	~1400[c]	1230[c]	~1500[c]	~200[c]	220[c]	~50%[t]
Thermal energy storage device [52]	~2000[c]	~480[c]	n.a	~1200[c]	~395[c]	n.a	~70%[t]
EHC [53]	n.a	n.a	42[e]	n.a	n.a	62[e]	~50%[t]
Coolant and lubricating oil heating [54]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	~20%[a]

[a] Cumulative emission reduction.
[c] Maximum concentration during cold start.
[e] Conversion efficiency.
[t] Light-off time reduction.

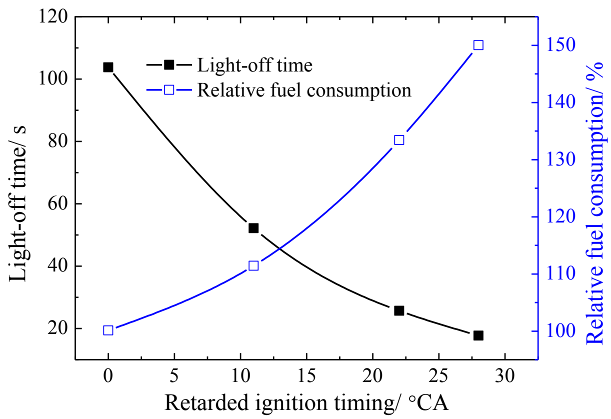

Fig. 1. Effect of retarded ignition timing on light-off time and relative fuel consumption (reproduced from Ref. [46]).

5.1.2. Compression ignition engines

The start of fuel injection influences the heat release rate, and is closely related to the engine power output and exhaust temperature. Similarly to the retarded ignition timing, the late fuel injection causes less fuel to combust in the power stroke, and more unburned fuel is emitted to the atmosphere. The SCR is usually positioned downstream of the DOC and DPF, which means that the expansion in the turbine and the long distance between the exhaust valve and the SCR lead to significant heat loss. Cavina et al. [64] optimised the start of injection (SOI) and the opening of a variable nozzle turbine (VNT) to achieve fast SCR temperature increase with limited fuel penalty. With the SOI control strategy in Ref. [60], the light-off time decreased from ~900 s to ~300 s with only 1.47% fuel penalty; however, 300 s are still a long light-off time.

5.2. Higher idle speed and load

Higher idle speeds imply more fuel injected into the cylinder, which means that additional exhaust energy heats the catalyst during warm up before being dissipated in the atmosphere, while fuel consumption increases. Fig. 2 shows the catalyst inlet temperature profiles for an SI engine at different idle speeds [35]. The temperature was still below 200 °C after a 75 s warm up at an idle speed of 1400 r/min. Even with the highest idle speed, the temperature ramp rate was insufficient to achieve fast catalyst light-off.

Compared with higher idle speed, increased load during the warm up of an HEV engine implies less fuel penalty and faster temperature increase [35]. The additional mechanical power can be used by the electric motor to recharge the HEV battery [65].

Ding et al. [66] improved the thermal management of the catalyst of a six-cylinder diesel engine by deactivating three cylinders and adopting “flexible valve motion” in loaded conditions. The cylinder deactivation increased the load of the three active cylinders, which caused lower exhaust flow rate at higher temperature. Only 2% fuel penalty was measured for an exhaust temperature increase from ~190 °C to ~310 °C, with respect to the six-cylinder operation without thermal management, while, a 39% fuel consumption reduction was achieved in comparison with the six-cylinder operation at ~310 °C. No fuel penalty was obtained when the cylinder deactivation was combined with “flexible valve motion,” while the exhaust temperature increased from ~120 °C to ~200 °C. Based on these results, such method is practical to achieve fast catalyst light-off without additional fuel consumption.

5.3. Variable valve timing, wastegate control, variable nozzle turbines and variable geometry turbines

Variable valve timing (VVT) has been widely applied by the automotive industry to improve engine performance. VVT is also an alternative method to increase exhaust temperature during cold start. In fact, late intake valve opening (IVO) implies less fresh air into the cylinders, which leads to richer air/fuel mixture in CI and GDI engines, while early exhaust valve opening (EVO) reduces the exhaust expansion and increases its temperature. These two measures cause post-oxidation and fast catalyst light-off, which in Ref. [47] contributed to ~30% HC emission reduction with respect to the baseline engine (Fig. 3). As HC is one of the main ingredients of PM, in the same study the HC reduction also caused a ~28% PM reduction. The decrease of PM, especially evident during cold start, is mainly related to the nucleation mode particles that consist of inorganic salt and organic compounds. The drawback is that both late IVO and early EVO reduce thermal efficiency. Roberts et al. [67] adopted early EVO for the thermal management of the catalytic converters of a CI engine. The exhaust temperature increase ranged from 30 °C to 100 °C for early EVO values from 0° to 90° with respect to the calibration value, bringing a ~5% decrease of brake thermal efficiency during warm up for the 90° case.

Modern IC engines tend to have turbines with high expansion ratios to increase power density. The exhaust temperature significantly decreases after the expansion in the turbine, especially in cold start conditions, when the volute and blades of the turbine are cold. During warm up an effect similar to that of early EVO can be achieved by: (i) appropriate control of the wastegate opening to partially bypass the turbine; (ii) a variable nozzle turbine (VNT); or iii) a variable geometry turbine (VGT), where (ii) and (iii) increase the opening. However, all these methods imply substantial reductions of the available engine power in cold start conditions. The e-boost [68] could attenuate this effect, by using the electric supercharger during cold start and the turbocharger after engine warm up. As the literature on the topic is very limited, the e-boost application needs further investigation to discover

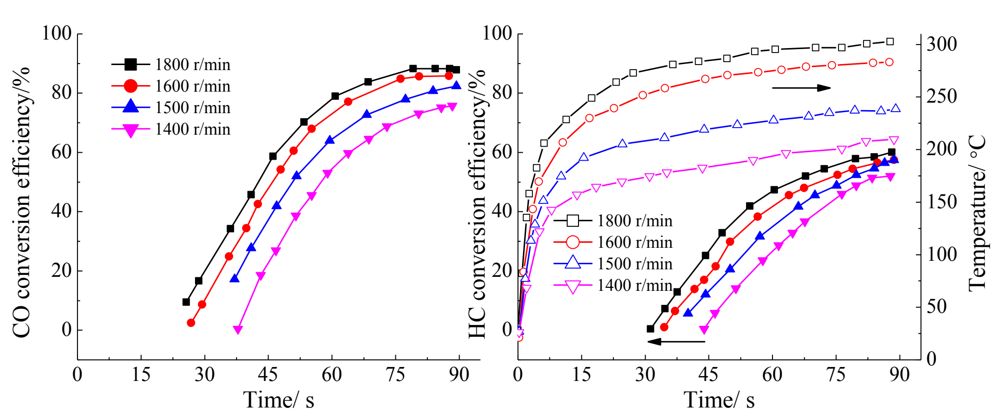

Fig. 2. The effect of idle speed on the TWC conversion efficiency (reproduced from Ref. [35]).

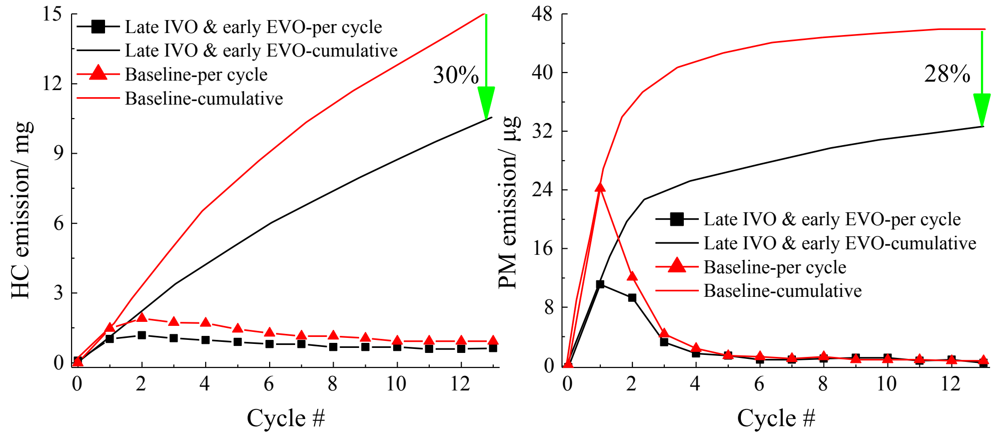

Fig. 3. Cycle-by-cycle and cumulative HC and PM emissions (reproduced from Ref. [47]).

its potential.

5.4. Air/fuel ratio adjustment

Enriching the air/fuel mixture is another method to increase the exhaust temperature and accelerate catalyst light-off [69]. It should be noted that after enrichment the air/fuel ratio is still lean for CI engines, while the ratio is rich for SI engines.

Enriched mixtures increase CO and HC engine-out emissions as the TWC efficiency is particularly poor during warm-up [24]. The air/fuel ratio can be increased through late IVO, as described in Section 5.3, and throttle adjustment. Late IVO is not an available option if the engine runs at high load.

Enriched air/fuel mixtures cause unburned HC and CO. As the temperature near the exhaust valve is high enough, secondary air injection into the tailpipe can alleviate the HC increase. For example, Lee [70] applied enriched air/fuel mixture and secondary air injection to an SI engine in the first 25 s of the FTP-75 driving cycle, as the majority of the emissions are produced at the beginning of the driving schedule. Moreover, the secondary air injection can increase the exhaust flow rate and decrease the exhaust temperature at the catalyst inlet. Hence, the cold air injection must be sufficiently far from the catalyst inlet, and applied at the optimal rate for the specific engine condition. Fig. 4 shows the effect of the equivalent air/fuel mixture ratio and secondary air injection rate on CO and HC emissions. The CO reduction in the catalyst increased with the equivalent ratio without the secondary air injection, because there was less oxidant in the exhaust after the mixture was enriched. For a given equivalent ratio, the pipe-out CO concentration decreased with the secondary air injection because of the post-oxidation and improved thermal condition of the catalyst. After the secondary air injection, thermal oxidation (CO and HC oxidation upstream of the catalyst) increases especially for higher air injection rates, with CO thermal oxidation percentages from cylinder to catalyst in excess of 50% [70]. For high equivalent ratios, also the catalyst light-off performance improves with the secondary air injection. The CO and HC oxidation before the catalyst releases significant heat, which further contributes to the exhaust temperature increase. High equivalent ratios lead to shorter light-off times but more pipe-out emissions, and secondary air injection alleviates the emission deterioration. For example, in the first 25 s of the FTP-75 driving cycle, the cumulative pipe-out emission is worsened after adopting these methods. The cooling effect of the secondary air injection is compensated if the injected air is preheated. In Ref. [8] the secondary air was preheated without additional energy consumption, by using the exhaust after the catalyst, which had a relatively low temperature after the SCR device, but was still hotter than the injected air. Other measures, such as thermal insulation, should be combined to alleviate emission deterioration when fuel enrichment is used. When the IC engine runs at the stoichiometric ratio, the catalyst is not in its best operating condition and typically has an efficiency of 40%~50%.

Air/fuel mixture enrichment is a commonly used technique. However, Nakayama et al. [48] adopted an air/fuel ratio leaner than 15.5 in an SI engine with the assistance of VVT and electronically controlled lift to increase the catalyst temperature. Valve timing and lift controlled the lean combustion and retarded ignition during cold start. The lean engine operation could increase the intake air velocity and enhance fuel atomisation, further increasing the burning rate. The HC reduction reached 45% when the air/fuel mixture was 5% leaner than the stoichiometric ratio.

5.5. Discussion

Because of their significant fuel penalty, the engine parameter based methods have a limited potential as thermal management methods on their own, although these techniques do not require any additional heating device. In fact, with the current focus on CO_2 emission reduction, these are low performance methods, and can be combined with the thermal management methods presented in the next sections. Moreover, based on the rather variegated data from the literature, which are difficult to compare, objective evaluation indices should be put forward and systematically used to evaluate the effect of such methods on catalyst performance improvement, for example in terms of light-off time reduction and cumulative emission reduction per unit of additional energy consumption.

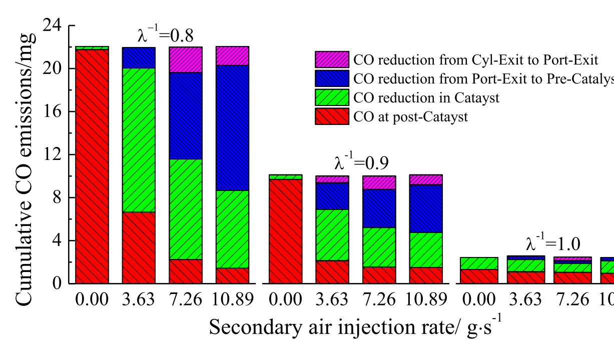

Fig. 4. Effect of the equivalent ratio and secondary air injection rate on CO emissions along the FTP-75 driving cycle (reproduced from Ref. [70]).

6. Catalyst heating methods independent of engine parameters

6.1. After-treatment system layout

The after-treatment system layout has a major influence on the thermal behaviour of the catalyst. For example, in Ref. [35] the variation from 28 cm to 15 cm of the pipe length between the exhaust outlet and the catalyst inlet reduced the light-off time from more than 180 s to less than 80 s. The reduction of the pipe length effectively decreases the heat loss, but can provoke overheating and thermal sintering in normal conditions, with irreversible catalyst damage. Fig. 5 shows the performance of CSF and CR-DPF systems [71], and also indicates the importance of the after-treatment system layout. In Ref. [77] the CR-DPF and CSF systems achieved continuous regeneration from a temperature of 270 °C. The continuous regeneration temperature decreased to 250 °C when the DOC and CR-DPF were jointly used, because of the DOC catalytic reaction and high NO_2 concentration.

According to Miao et al. [49], the best way to reduce the SCR light-off time was to decrease the thermal inertia of the catalyst and move the SCR upstream. In Ref. [72] the SCR was positioned at the downstream side of the DOC, and a heating device was coupled with the DOC inlet, such that the SCR could benefit from the higher exhaust temperature induced by the heater and the heat release of the HC oxidation in the DOC. During the FTP-75 driving cycle from cold conditions, the SCR reached the operational temperature within 100 s, and the NO_x emission reduction was in excess of 90% between 150 s and 300 s. The thermal behaviour of the DPF was deteriorated when the SCR was located at the DOC downstream, because of the heat absorption of the urea hydrolysis. The DPF and SCR layout had a minor influence on the PM removal efficiency, but it affected the DPF regeneration conditions. Miao et al. [49] coupled two small DOCs with the catalytic DPF and SCR, to simultaneously improve their thermal dynamics, with a compromise between DPF regeneration and SCR light-off time. We believe that, similarly to the solution in Ref. [49], two smaller heaters could be positioned before the DOC and SCR. The first heater would shorten the DOC light-off time, while the second heater would significantly improve the SCR thermal dynamics. The power distribution between the two heaters should be based on the appropriate prioritisation of the emission reduction (HC, CO and NO_x).

6.2. Burners

Similarly to enriched air/fuel mixtures combined with secondary air injection, after-burner devices form combustible mixture in the tailpipe. Ma et al. [50] used an after-burner to improve the thermal conditions of the catalyst, and achieved catalyst light-off in less than 20 s. Additional fresh air was injected into the exhaust manifold, coupled with unburned fuel, obtained through appropriate engine calibration, to form the combustible mixture. The combustion temperature of the mixture in the after-burner is hard to control, which may lead to catalyst damage and thermal sintering. Moreover, although the catalyst light-off time is shortened, this method brings significant fuel penalty. Being independent of the operating conditions of the engine, the extra burner allows flexibility in terms of heat injection position. Akcayol et al. [73] analysed an extra burner heated catalyst applied to an SI engine. The burner provided excellent emission reduction performance.

In Ref. [74] a diesel vaporiser without secondary emissions was designed to minimise the complexity and cost of the catalytic DPF regeneration system during cold start. The theory behind this method is the same as for burners. Vaporised diesel fuel is injected into the exhaust system, so that that the diesel fuel is oxidised by the DOC with heat released, resulting in DPF regeneration. Compared with the engine parameter based regeneration, the fuel penalty could be reduced by 50%. This system has the advantages of fast response, low fuel consumption and no effect on the engine power output. Singh et al. [75] also indicated that the delayed regeneration, with additional PM cumulated in the DPF, decreased the energy consumption.

6.3. Reformers

Similarly to the extra burners, reformers do not rely on the engine operating conditions. Kirwan et al. [51] used an on-board reformer to decrease cold start emissions by pyrolysing the gasoline in rich air/fuel conditions (richer than the stoichiometric value). The reformer provided an on-board H_2 source at high temperature. Part of the reformed gas was introduced into the cylinder to improve the combustion, and the remaining part was injected into the exhaust to heat the catalyst. Such method causes excellent engine-out and pipe-out emission reduction during cold start, at the price of a large fuel penalty. Moreover, only 10–15% of the gasoline is reformed, and large amount of heat is transferred to the tail-pipe and atmosphere. To decrease the heat loss in the tailpipe, the heat injection position can be close to the catalyst inlet. H_2 in the cylinder promotes flame propagation, which improves combustion efficiency with less unburned fuel. Reformers preheating the catalyst inlet encounter similar problems of fuel penalty and higher CO_2 emissions. Reformers operate independently from the IC engine, with no influence on its power output. The reforming system needs an additional reactor and a fuel supply system, which imply high costs and complexity.

In Ref. [76] a partial oxidation (POX) system, i.e., a small combustion device, was introduced to convert liquid fuel into gaseous species. This system replaced the fuel supply of the engine during cold start, with 40–80% HC and CO emission reduction.

6.4. Thermal insulation methods

During cold start and warm up, the quenching and crevice effects on the cylinder wall and piston head are serious, and lead to high engine-out emissions, especially for SI engines. Cerit et al. [77] analysed the effect of partially ceramic coated pistons on the cold start emissions of an SI engine. In the specific application, the temperature of the ceramic coating area increased by 100 °C, with a ~15% reduction of the peak values of HC emission. Higher cylinder temperatures improve combustion and increase exhaust temperature. In the last century, the adiabatic diesel engine was investigated to decrease the thermal loss and improve the thermal efficiency, with the result of high exhaust temperatures [78].

Similarly to ceramic coated pistons and adiabatic diesel engines, thermal insulation methods are an alternative solution to improve the catalyst thermal behaviour by decreasing the exhaust heat loss during warm up. Although this method leads to significant thermal load and demanding specifications for the thermal insulation material,

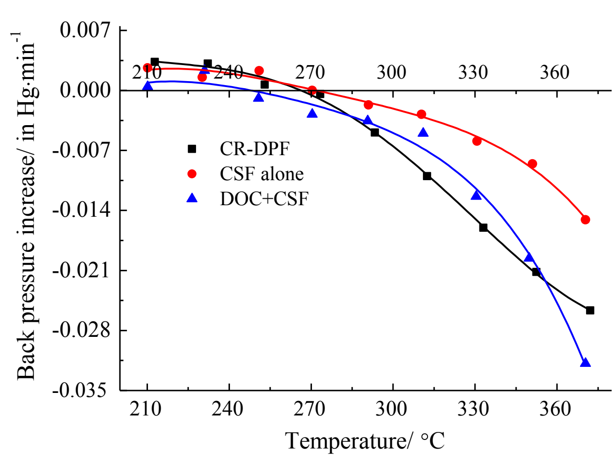

Fig. 5. Back pressure increase as a function of temperature for three DPF regeneration systems (reproduced from Ref. [71]).

decreasing the catalyst heat loss through thermal insulation is more practical than thermally insulating the engine. In fact, a thermal insulation material on the catalyst wall can effectively decrease the heat loss [79,80]. Nevertheless, in our opinion, such option needs to be further demonstrated through simulations or experiments, as it can provoke issues after catalyst light-off.

Burch et al. [79] proposed vacuum insulation and thermal storage based on phase changing materials to enhance the heat retention of a catalytic converter. Compared with thermal insulation materials, vacuum insulation could effectively alleviate the thermal hysteresis caused by the thermal capacity of the insulation material. Also, a metal hydride, with a controllable thermal conductivity ranging from 0.49 to 27 W/m^2 K, was used to prevent catalyst overheating. The heat stored in the phase changing material during the vehicle operation reduced the light-off time with no energy penalty. The vacuum insulation of the catalytic converter was also simulated by Daya et al. [80], with results showing 26% and 48% CO and HC emission reductions during warm up. According to [81], such method can keep the catalyst temperature above 300 °C for at least 12 h once the IC engine is switched off. In addition to decreasing the heat loss, catalyst carrier materials with low thermal capacity, i.e., typically ceramic materials, have a high temperature ramp rate for the same absorbed heat. Metal carriers have low thermal capacity, however they are usually implemented in a fragile honeycomb structure, and require a noble material coating, which is rather difficult to manufacture.

6.5. Heat storage materials

Gökçöl et al. [61] reviewed energy storage systems based on phase changing materials for IC engine and catalyst preheating, including analysis of the suitable storage materials and the structure of the devices. However, the equipment is complex, and is difficult for phase changing materials to keep the temperature high for long, i.e., when the IC engine is off. Also, it takes significant time to store the thermal energy if the phase changing material is cold. Such devices are more practical for vehicles running regularly for long time at low speed, for example urban buses and airport shuttle buses.

6.5.1. Application to the IC engine

IC engines waste almost 50% of the heat through the exhaust, coolant and lubricating oil. Heat storage materials can be used to partially recuperate thermal energy after the engine is warm, for preheating the IC engine, i.e., for warming it up before it is switched on.

Gumus [52] used $Na_2SO_4 \cdot 10H_2O$ as heat storage material to preheat a four-cylinder gasoline engine through its coolant, so that the engine temperature increased by 17.4 °C, with 64% and 15% reduction of the CO and HC concentrations at the engine output. Coolant preheating increases the cylinder and piston temperatures, which decreases the quenching and crevice effects on the engine-out emissions, improves the air/fuel mixture and increases the exhaust temperature. In the example shown in Fig. 6, the emission reduction in the exhaust pipe was caused by the improved post-oxidation and catalyst performance. In the first 420 s the combustion improvement dominated the emission reduction. The HC concentration difference before and after the catalyst became more significant once the catalyst reached 200 °C. The exhaust temperature benefit achieved through coolant preheating was limited, i.e., preheating had a weak effect on catalyst performance, while it enhanced fuel economy by improving combustion. In our opinion, coolant preheating should be combined with catalyst preheating to simultaneously increase engine and catalyst temperatures.

The benefits of preheating the engine also include reduced friction losses. This aspect is especially important during warm up, when, because of the low temperature, the viscosity of the lubricating oil is usually high, which increases the friction mean effective pressure (FMEP) and leads to low mechanical efficiency [82].

6.5.2. Application to the catalytic converter

Korin et al. [83] investigated a thermal capacitance based on phase changing materials, integrated into the catalytic converter to maintain the catalyst temperature during engine stops. The phase transition temperature was slightly higher than the catalyst light-off temperature. Under normal operating conditions, part of the thermal energy of the exhaust gas was stored in the device, which preheated the catalyst before the engine was switched on. This method has the advantage of not causing additional energy consumption. However, the heating profile associated with the device is not flexible and the temperature ramp rate depends on the hardware design. What is worse, the catalyst light-off time will be prolonged if the heat storage material is cold after a long engine stop. Gumus et al. [84] showed that the case study heat storage system worked only for engine stops shorter than 15 h.

6.6. Electrically heated catalysts

Electrically heated catalysts (EHCs) are an effective method to reduce exhaust emissions and fuel consumption. Andre [85] observed that the temperature of the lubricating oil and coolant in one third of the considered trips (a database of 55 vehicles along 10,000 trips was considered) was lower than the fully warm level, which promoted the EHC adoption during cold start and warm up. Knorr et al. [86] highlighted the potential CO_2 and exhaust emission reduction benefits for HEVs equipped with EHCs coupled with advanced emission control strategies.

Pace et al. [60] indicated that the thermal energy to cause a given catalyst temperature increase through an EHC device is ~40% of the energy of the additional injected fuel for achieving the same effect through an engine parameter based method. In fact, an electric heater

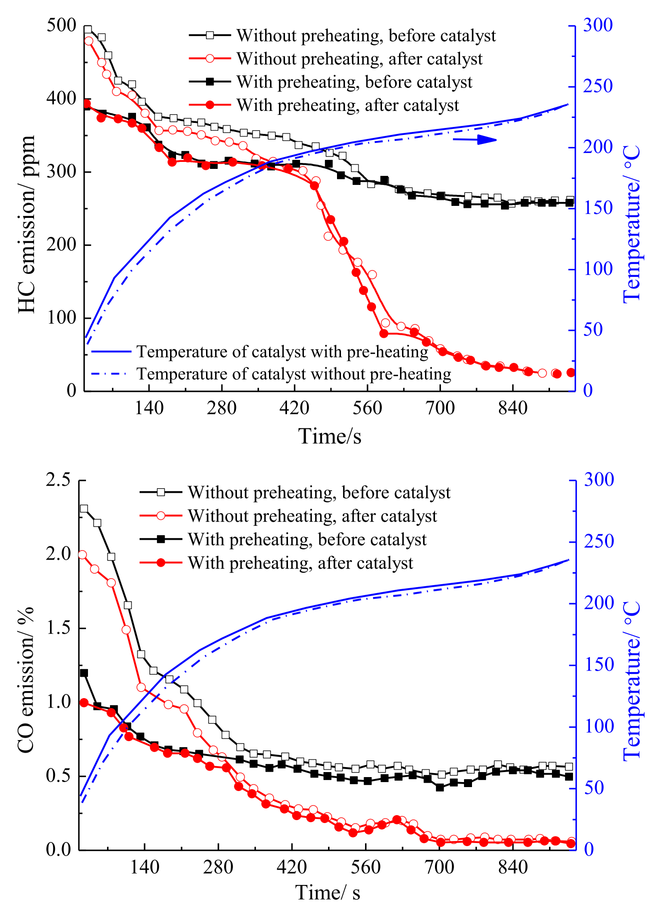

Fig. 6. Examples of HC and CO emission profiles with and without preheating (reproduced from Ref. [52]).

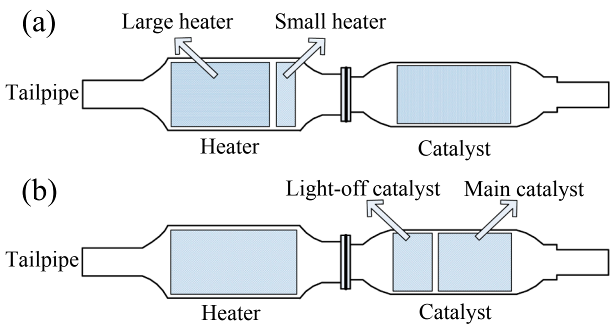

Fig. 7. Two novel EHC configurations (reproduced from Ref. [91]).

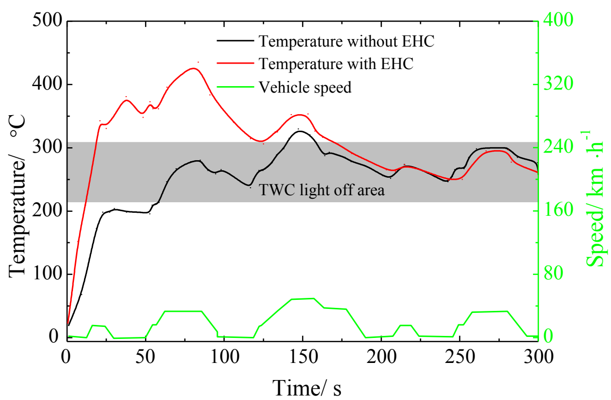

Fig. 8. Exhaust temperature and vehicle speed profiles with and without EHC during a part of the NEDC (reproduced from Ref. [42]).

can directly heat the catalyst rather than the exhaust, and less energy is wasted with respect to the engine parameter based methods. Overall, EHCs provide high efficiency and are considered compatible with the 2020 CO_2 targets [87]. The transient response of EHCs is better than for thermal energy storage, because of their heat injection flexibility and independence from the IC engine operating conditions. EHCs are especially convenient in HEVs, in which they consume the energy stored in the battery during regenerative braking and cruising. Nevertheless, the EHC consumes electric energy, which is eventually generated from fuel consumption. As the literature does not cover such topic in detail, the overall efficiency improvement associated with the EHC, in comparison with other methods such as additional fuel injection, needs further investigation.

With respect to the EHC configurations, Pfahl et al. [88] integrated a heater into a hydrolysis catalyst with upstream urea injection to achieve a 65–70% NO_x conversion rate. This method could effectively resolve the urea evaporation and hydrolysis problems during cold start. As the heating position for the hydrolysis catalyst was at the downstream of the DPF and the DPF regeneration temperature was much higher than that of the SCR, extra thermal management methods could have been implemented for fast DOC and DPF light-off, such as another heater or post injection. Culbertson et al. [89] adopted the same method with an effective control strategy to decrease the NO_x emissions during cold start and manage the exhaust temperature for improving the catalytic process [89]. The combination of DOC and CSF was effective to achieve DPF regeneration without additional heat injection when the DOC was operating above its light-off temperature [90]. However, the same setup was ineffective during cold start; hence, heat injection was necessary to achieve DPF regeneration. Williamson et al. [91] developed a catalytic DPF regeneration device based on an electrical heater integrated with the DPF to heat the upstream exhaust. Gonze et al. [92] implemented a cold start heating system for a diesel engine, targeting the thermal management of the SCR and NO_x emission reduction. The heating element was positioned at the SCR inlet with a control strategy based on the SCR temperature.

A novel EHC configuration was proposed in Ref. [93], in which the device consisted of two heaters with different volumes and heating powers, as shown in Fig. 7(a). The larger one was used for heating the catalyst during cold start and warm up, while the small heater was more often used in the regular start-stop conditions to keep the catalyst in its high efficiency region, i.e., for post-heating. However, it should be noted that the larger heater was located at some distance from the catalyst, which may lead to additional energy loss during cold start. Alternatively, the whole heating device could consist of several small volume units, to be switched on and off depending on the operational requirements.

In order to achieve fast catalyst light-off, Ramanathan et al. [93] also divided the TWC into a smaller light-off catalyst and a main catalyst, as shown in Fig. 7(b). Such configuration shortened the catalytic converter light-off time because of the small thermal capacity of the light-off catalyst, which was activated first. The catalytic reaction of the light-off catalyst provided extra thermal energy for heating the main catalyst. Due to the small volume of the light-off catalyst, the temperature increase can be rather rapid, which, without appropriate control, enhanced the possibility of thermal sintering.

Fig. 8 shows an example of exhaust temperature profile with and without EHC during a part of the NEDC [42]. The EHC shortened the TWC light-off time from 60 s to 15 s, and the maximum temperature value was 430 °C. The system response would have been further improved by a more advanced EHC control strategy, as the specific controller applies a constant heating power well beyond the catalyst light-off.

Horng et al. [94] compared the light-off times with an EHC and a fuel enrichment method, and found that the time with the EHC was less

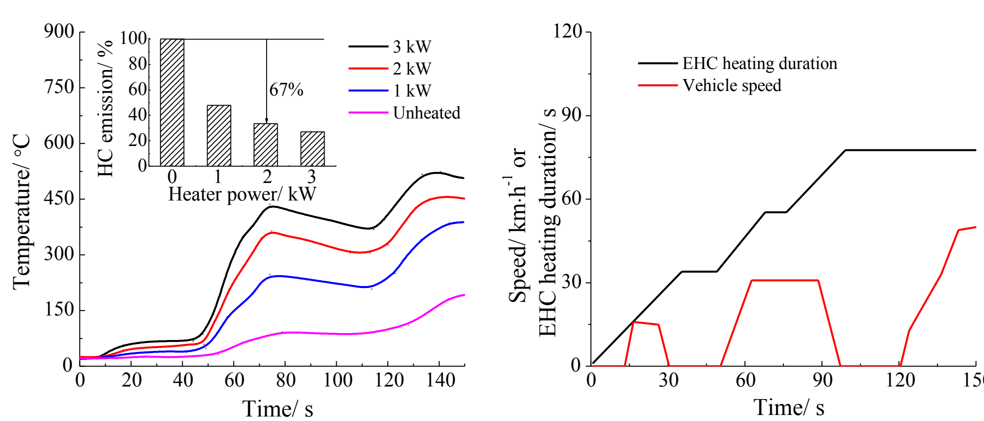

Fig. 9. Cumulative HC emissions with different heating power levels of the EHC (reproduced from Ref. [92]).

than 180 s, shorter than through fuel enrichment. In the EHC, the heater power determines the profile of the exhaust temperature increase. Cumulative HC emissions for different EHC heating powers are shown in Fig. 9 [92]. The specific catalyst took only 60 s to reach 200 °C with a heating power of 3 kW, 70 s for 1 kW, and 150 s without EHC. The cumulative CO emission reduction was more than 50% for the 1 kW case.

In general, most of the currently proposed EHC heating control strategies are rather basic, i.e., they do not consider engine conditions and exhaust temperature. A poor control strategy may also cause thermal sintering of the catalyst. Ideally, the EHC heating power should vary with the exhaust temperature profile and flow rate through continuous feedback control, rather than being constant, e.g., the power may decrease during warm up. Also, the EHC should be switched off after the engine reaches its warm condition, rather than operating for a constant duration. We believe that further work should be carried out to implement more advanced EHC controllers and devices, based on a trade-off between exhaust temperature increase, energy and fuel consumption, catalyst efficiency and thermal sintering prevention. Such EHC controllers should be holistically designed, to integrate the engine parameter based methods as well. For example, in conditions of high engine load, the power output should have the priority even at the cost of catalyst performance. Moreover, model predictive strategies including consideration of the expected vehicle operating profile should be evaluated. Finally, appropriate EHC performance indicators should be proposed, for example in terms of cumulative emission reduction per unit power (%/kW) and light-off time reduction per unit power (s/kW).

6.7. Improved thermal management of the coolant and lubricating oil

The coolant and lubricating oil warm up time greatly influences the IC engine and catalyst performance. In fact, fast engine warm up decreases the catalyst light-off time. Effective methods to achieve fast coolant warm up are based on electric heaters controlled by thermostats [95], electric pumps [96] and heat storage materials [61]. For example, in Ref. [54], ~10% HC and ~20% CO emission reductions were obtained with an electric coolant pump, which adjusted the coolant temperature from ~90 °C to ~110 °C. An electric heater, controlled by a thermostat, preheated the coolant before engine cranking, which significantly decreased the engine warm up time. For heat storage materials the reader can refer to Section 6.5.

Similarly to the coolant, low oil temperature causes high lubricant viscosity, which leads to high fuel consumption and emissions. For a specific application, the maximum friction losses in the warm up process were 2.5 times higher than in warm conditions [97]. Waste heat recovery [98], heat storage materials [52] and controllable electric oil pumps [99] were used to enhance the thermal dynamics of the oil. Di Battista et al. [98] indicated that the maximum exhaust temperature increase was in excess of 200 °C after using a heat exchanger to heat the oil with the waste heat from the exhaust. This was also beneficial to the thermal dynamics of the coolant.

The conclusion is that coolant and lubricating oil heating can accelerate catalyst light-off. The effect of coolant and lubricating oil heating on catalyst thermal conditions should be further explored to optimise catalyst performance during cold start, possibly including thermal management methods of the catalytic converter as well.

7. Conclusions

IC engine emissions are associated with environmental and health problems, which have led to the promulgation of stricter emission regulations. Significant emission reductions have already been achieved for engines operating in normal conditions. However, the emissions during cold start and warm up are still significant, because of the serious engine-out emissions and weak catalyst performance due to the low cylinder and exhaust temperatures. Based on the available data, in cold start conditions the maximum pipe out concentrations of CO and HC range from ~950 ppm to ~8400 ppm and from ~220 ppm to ~28000 ppm, respectively.

This paper reviewed thermal management methods for fast catalyst light-off, with the purpose of decreasing cold start and warm up emissions. The literature shows that through appropriate methods the catalyst light-off time improvement was in the 20–90% range, while the reduction of the maximum emission concentration exceeded 90%.

Burner devices and engine parameter based methods shorten the catalyst light-off time by improving its thermal management, further decreasing exhaust emissions in cold start and warm up conditions. However, these methods often imply high fuel penalty as significant heat is transferred to the atmosphere though the tailpipe, particularly when the engine is far from its optimal operating conditions. For example, the heat loss through the turbine volute is an important factor causing exhaust temperature decrease, and thus low catalyst temperature. Measures such as wastegate, VGT and VNT can be applied to decrease the expansion ratio during cold start and warm up, but they may cause engine power reduction and additional fuel consumption. From a technical viewpoint, the e-boost has the potential to be a better solution to balance exhaust temperature, engine power output and fuel economy.

Compared with the previous methods, thermal management using heat storage materials resolves the trade-off between energy consumption and emission reduction by preheating the engine coolant, lubricating oil and catalytic converter. However, in general, such techniques bring limited benefits in terms of catalyst performance improvement. Heat storage systems are more practical for vehicles that are frequently used, to prevent the heat storage material from losing its heat.

Thermal insulation material coatings can be applied to the catalyst and exhaust pipe, for reducing the heat loss. Low thermal capacity materials for the catalyst carrier are useful to swiftly increase the catalyst temperature. However, they also increase the risk of thermal sintering.

With the most obvious advantage of flexibility of heat injection in terms of position and flux, EHCs are also characterised by high energy utilisation efficiency and low thermal energy transfer to the atmosphere. EHCs have excellent catalyst light-off time reduction capability and effectively decrease exhaust emissions. A lack of advanced EHC control strategies was identified in the survey, together with a gap in terms of evaluation indices for the objective assessment of the thermal management of the catalyst. Such indicators should consider the trade-off among light-off time improvement, cumulative emission reductions and fuel consumption, e.g., they could include the cumulative emission reduction per unit power (%/kW) and the light-off time reduction per unit power (s/kW). Moreover, multiple thermal management methods should be combined to optimise the thermal behaviour of the catalyst, and integrated model predictive control strategies should be introduced and assessed to further improve performance.

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Appendix A. Supplementary material

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