EUROPEAN MECHANICAL SCIENCE

Research Article

e-ISSN: 2587-1110

Enhanced after-treatment warm up in diesel vehicles through modulating fuel injection and exhaust valve closure timing

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Abstract: Exhaust after-treatment (EAT) units in diesel engine systems necessitate high exhaust temperature (above 250°C) to perform effectively and reduce the emission rates sufficiently during operation. Several methods such as exhaust throttling, early exhaust valve opening and late post fuel injection require high fuel penalty (mostly above % 10) to sustain EAT systems above 250°C. The aim of this numerical work is to combine delayed fuel injection and advanced exhaust valve closure in a diesel engine model to reduce the fuel penalty below % 10 as exhaust temperature is improved over 250°C. Fuel injection timing (FIT) is delayed up to 13°CA degrees from the nominal position. Exhaust valve closure is simultaneously advanced up to 30°CA degrees from the baseline as fuel injection is delayed in the system. Numerical results demonstrated that retarded fuel injection improved exhaust temperature moderately and needed relatively high fuel penalty. Unlike FIT modulation, early exhaust valve closure (EEVC) enhanced engine-out temperature effectively and required lower fuel penalty. However, EEVC caused a significant exhaust flow reduction, affecting EAT warm up negatively. Simultaneous application of EEVC and delayed FIT decreased the exhaust flow rate less than that in EEVC alone mode. Moreover, it kept fuel penalty below % 10, which was not found possible with RFI method alone in the system. EEVC + RFI combined method was also seen to heat up the EAT unit above 250°C in a fuel saving manner compared to RFI alone mode.

Keywords: diesel engines, late fuel injection, early exhaust valve closure, exhaust temperature, after-treatment warm up.

1. Introduction

Nowadays, many engine producers utilize EAT systems for diesel engines to decrease the harmful emission rates and meet the strict regulations issued by environmental agencies [1, 2]. EAT units are highly helpful in curbing emission rates. However, post-treatment units such as SCR, LNT and DOC are highly temperature-dependent and they tend to work effectively when they are adequately heated up to a certain temperature (~ 250°C) [3, 4]. The SCR unit, in particular, enables the desirable, effective NOx conversion between temperatures of 250°C and 450°C [5]. That high temperature requirement is problematic for diesel engines since exhaust temperature cannot be kept over 250°C particularly at low loads and thus, EAT units operate ineffectively [6]. There is a significant need for those loads to elevate exhaust temperature and enable improved EAT systems [7].

One effective approach to obtain high exhaust temperature is to implement variable valve timing (VVT) in compression-ignition engine systems [8–10]. Control of intake valve closure and exhaust valve opening is particularly useful for boosting exhaust-out temperature at low engine loads [11–13]. Negative valve overlap (NVO) via modulation of intake opening and exhaust closure is also found to be beneficial to elevate EAT inlet temperature in diesel engines [14, 15] as it partially traps the exhaust gas inside the cylinders [16]. Joshi et al. experimentally implemented NVO in a 6-cylinder diesel engine and achieved an exhaust temperature rise of 40°C with reduction in NOx rates by % 60 through internal exhaust gas recirculation [17].

In addition to engine valve timing actuation, some different fuel injection techniques can be investigated to achieve superior EAT thermal management [18]. One common method in this category is retarded fuel injection (RFI) [19]. Cavina et al. elevated exhaust temperature by 48°C through delayed SOI (15°C A from the baseline) in a 4-cylinder diesel engine system. However, it required % 15 rise in fuel consumption, which is considerable, to

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Cite this article as:
Başaran, H. (2024). Enhanced after-treatment warm up in diesel vehicles through modulating fuel injection and exhaust valve closure timing. *European Mechanical Science, 8*(2): 93-103. https://doi.org/10.26701/ems.1441861

History dates:
Received: 23.02.2024, ***Revision Request***: 24.04.2024, ***Last Revision Received***: 09.05.2024, ***Accepted***: 24.05.2024

achieve such an exhaust temperature improvement [20]. RFI deteriorates combustion effectiveness due to delayed injection timing, but it has the advantage of moderately improved exhaust temperature at low loads [21]. Close and late post-injection are other fuel injection-based techniques to enhance the outlet temperature. Post-injection rate and timing are generally seen to be directly related to the exhaust temperature [22].

Some engine-independent methods are continuously explored by researchers to improve exhaust temperature as well [23]. Electrical heating is one of the most promising of those outer-engine techniques [24]. After-burners and heat storage units are seen to enhance EAT thermal management too [25, 26]. Those methods necessitate additional energy supply and extra equipment to be positioned on the engine system [27] and therefore, mostly increase the manufacturing costs. However, those techniques also enable flexible and quick EAT heat up in diesel engine systems, which is a significant advantage in maintaining low emission rates.

In this work, delayed fuel injection is combined with advanced exhaust valve closure in a 1-D engine simulation model to achieve effective exhaust thermal management. Although those two techniques are separately beneficial to improve EAT thermal management, simultaneous implementation of them reduces the fuel penalty the system suffers to reach efficient EAT and thus, reduces emission rates.

2. Material and Methods

In this work, thermal management of exhaust unit of a diesel engine system is improved via proper adjustment of engine parameters. A previously validated simulation model is used in the analysis [11, 28]. The engine model and the technique applied in the model are explained in the following subsections.

2.1. Engine Model

The engine model created via using the Lotus Engine Simulation program [29] is demonstrated in Figure 1. It is operated with active six cylinders and each cylinder has double inlet and double exhaust valves. Those types of diesel engines are commonly utilized in commercial lorries and public buses, which require the exhaust unit warm up to keep emission rates at low levels. The focus in this study is to modulate the engine valve timing (mainly exhaust valve closure timing) and fuel injection timing to achieve that exhaust warm up in a fast and engine-dependent manner. It is desired to demonstrate that reasonable modulation of engine-specific components can be an alternative approach for rapid exhaust and thus, EAT unit warm up.

Properties of the diesel engine are given in Table 1. The valve timings in Table 1 are valid for nominal condition. The engine has single fuel injection and injection timing is also applied for base condition (1°CA BTDC), in which the system is operated at 1200 RPM engine speed and at 2.5 bar BMEP engine load. Compression ratio is maintained constant at 17.3 in all modes.

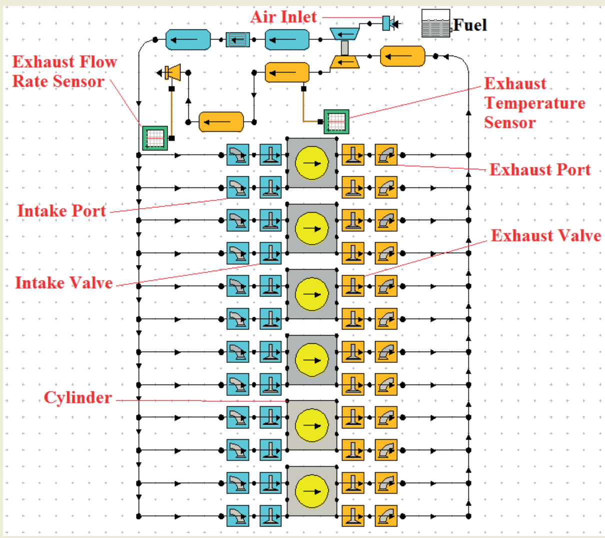

Figure 1. Engine model.

Table 1. Specifications of the diesel engine.

Bore (mm)	107
Stroke (mm)	124
Connecting rod length (mm)	192
Compression ratio	17.3:1
Exhaust Valve Opening	20°CA BBDC
Exhaust Valve Closure	20°CA ATDC
Intake Valve Opening	20°CA BTDC
Intake Valve Closure	25°CA ABDC
Start of Injection (SOI)	1°CA BTDC

2.2. Application of EEVC + RFI Technique

This work attempts to combine two different engine-based techniques to enhance the thermal management of the EAT unit in a diesel engine model. Fuel injection timing (shown as SOI timing in Table 1) and exhaust valve closure timings are the selected engine parameters to be modulated with the objective of improved ETM.

The change in EVC and SOI timing is demonstrated in Table 2. Those modulations are valid for EEVC_alone and RFI_alone modes. For those cases, only EVC or SOI timing is altered in the system. As seen in Table 2, exhaust unit is shut off earlier in the system as valve closure timings are steadily advanced and moved far from the starting EVC timing, 20°CA after top dead center (ATDC). For the last step, EVC timing is advanced to 20°CA BTDC, which is 40°CA earlier than the nominal (starting) timing. In addition to EEVC_alone mode, RFI_alone mode is also considered in Table 2. In that mode, SOI timing is retarded up to 12°CA ATDC with 2°CA increments.

For combined EEVC + RFI modes, change of EVC and SOI timing is shown in Table 3. SOI timing is modulated for 3 different EEVC cases in Table 3: EEVC (0), EEVC (5) and EEVC (10) in which EVC timing is advanced 20°CA, 25°CA and 30°CA from the nominal EVC timing (20°CA ATDC), respectively. SOI timing is altered differently for each of those modes to achieve 250°C exhaust temperature in the system. Since exhaust temperature is predicted to increase more at EEVC (5) and EEVC (10) cases, the delay in SOI timing is relatively lower at those modes compared to EEVC (0) mode. While SOI timing is retarded up to 13°CA ATDC in EEVC (0) mode, it only needs to be delayed up to 10°CA or 7°CA ATDC in other EEVC modes in Table 3. Overall, those different combinations are examined with the aim of further improving the EAT thermal management in comparison to EEVC_alone and RFI_alone modes.

3. Results and Discussion

Firstly, impact of RFI and EEVC methods is examined separately on the model. The improvement in exhaust temperature and the rise in fuel penalty in each method are analyzed. Then, effect of combined EEVC + RFI method on exhaust temperature, mass flow rate and fuel penalty is explicitly examined.

Effect of RFI on in-cylinder temperature is seen in Figure 2 below. Different RFI modes – RFI (3), RFI (7) and RFI (11) with SOI timing of 3°CA, 7°CA and 11°CA ATDC, respectively – are compared with nominal mode in this plot. It is seen that delayed fuel injection tends to increase the in-cylinder temperature far from the TDC due to the retarded combustion of the fuel. In-cylinder pressure is relatively low at those piston positions and thus, maximum in-cylinder temperature is not as high as the one achieved in nominal condition. However, the expansion of in-cylinder gas in RFI modes, particularly in RFI (7) and RFI (11), begins in a rather delayed position compared to nominal case in Figure 2. Therefore, it is observed that in-cylinder temperature can be maintained at relatively higher levels in expansion process via proper use of RFI technique.

As demonstrated in Figure 2 above, delaying combustion highly affects the behavior of the in-cylinder gas. The improved in-cylinder temperature due to RFI positively affects the average exhaust temperature at turbine exit,

Table 2. Change of SOI and EVC timing in EEVC_alone and RFI_alone modes.

Method	Engine parameter	Nominal value	Change in every step	Total number of steps	Parameter value in furthest step
EEVC_alone	EVC Timing	20°CA ATDC	5°CA advanced	8	20°CA BTDC
RFI_alone	SOI Timing	1°CA BTDC	2°CA delayed	7	12°CA ATDC

Table 3. Change of SOI and EVC Timing in different EEVC + RFI combinations.

Method	EVC Timing (Constant)	SOI Timing Interval	Change in SOI Timing	Total number of steps
EEVC (0) + RFI	0°CA BTDC	Between 1°CA ATDC and 13°CA ATDC	3°CA delayed	5
EEVC (5) + RFI	5°CA BTDC	Between 1°CA ATDC and 10°CA ATDC	3°CA delayed	4
EEVC (10) + RFI	10°CA BTDC	Between 1°CA ATDC and 7°CA ATDC	2°CA delayed	4

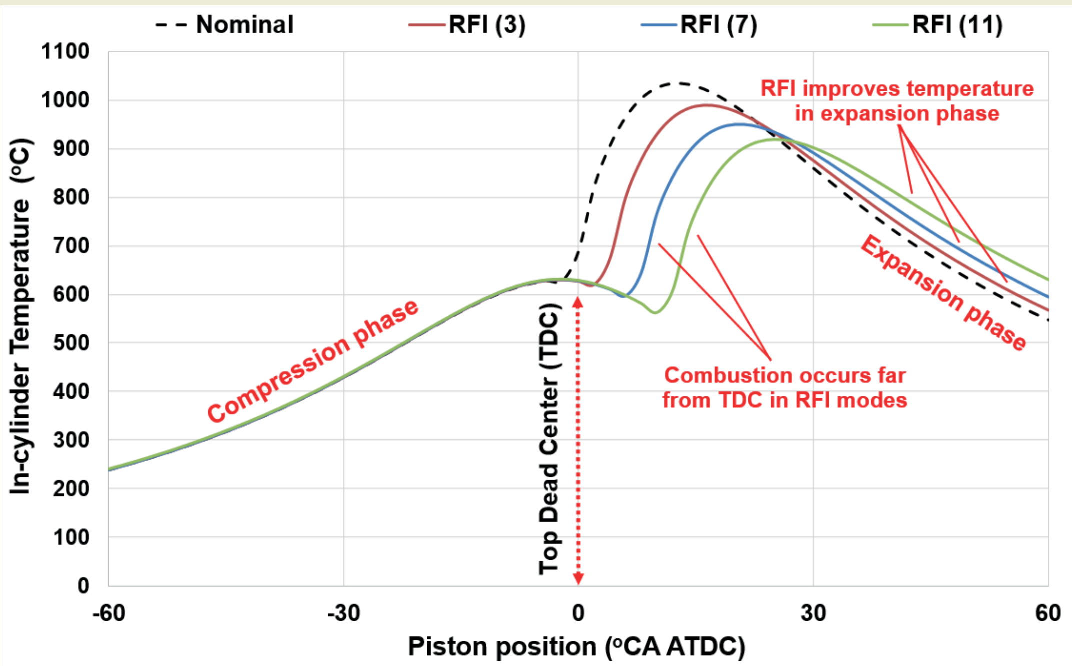

Figure 2. Effect of different RFI modes on engine in-cylinder temperature.

as shown in Figure 3 below. While the exhaust temperature is so close to 190°C at baseline, it approaches 225°C as RFI is aggressively applied in the system. As seen, exhaust temperature is increased steadily through retarded combustion. However, exhaust temperature cannot exceed 250°C, which is unable to keep EAT effectiveness at desirable levels. It is seen that fuel consumption is inevitably climbed as RFI is implemented in the system. The fuel consumption penalty in RFI modes in Figure 3 is calculated as the fuel increase percentage based on fuel consumption in nominal mode. It is obviously zero at nominal injection timing (1°CA BTDC), as this is the starting point in the analysis. It moves constantly upward as FIT is either moderately or extremely retarded from the nominal timing. The main reason for the undesirable fuel penalty in RFI mode in Figure 3 can be attributed to the ineffective combustion of the fuel due to low in-cylinder pressure. The more delayed the fuel injection timing is, the more additional fuel feeding is required for constant engine load. Even though the fuel penalty surpasses % 10, exhaust temperature still remains below 250°C. It can be derived that RFI is moderately effective in improving exhaust gas thermal management.

The rise in exhaust temperature via RFI technique is directly proportional with the fuel consumption penalty, as indicated in Figure 3. Therefore, when applied alone, use of extreme RFI is not desired to keep fuel penalty and emission rates below a certain level. Reasonable use of RFI seems to be more appropriate for EAT thermal management. The change of $IMEP_{gross}$ – gross power generating potential of the engine concerning mainly the closed cycle – and BMEP – net power generating potential of the engine concerning both closed and open cycles – in RFI mode in Figure 4 can be examined to understand the additional fuel need in the system.

Unlike previous plots, fuel injection rate is held constant

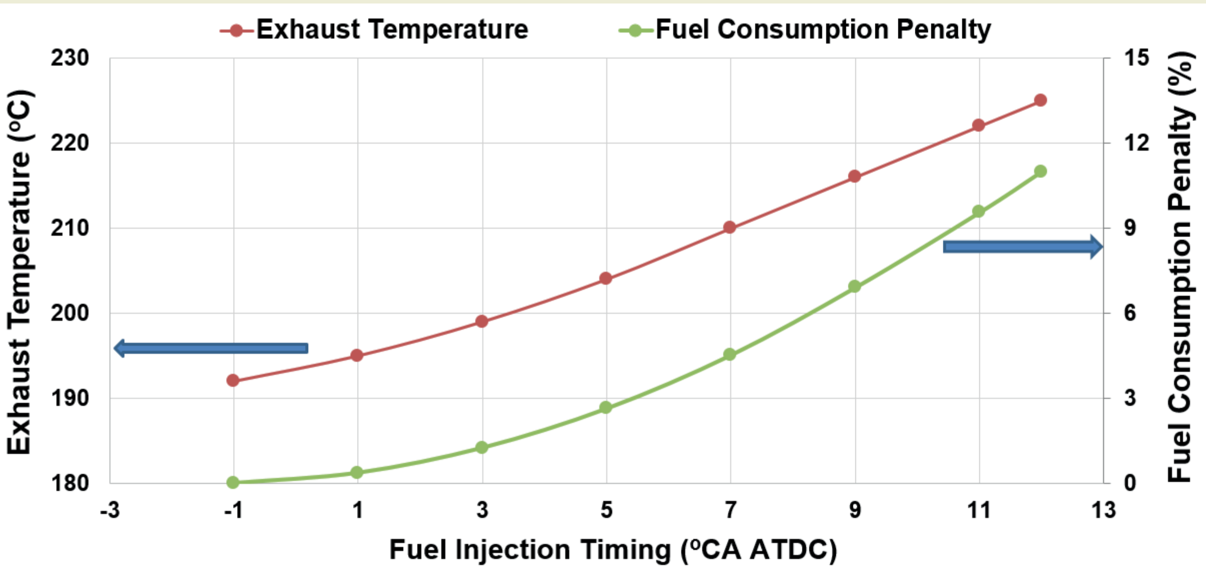

Figure 3. Effect of late fuel injection timing on exhaust temperature and fuel consumption penalty.

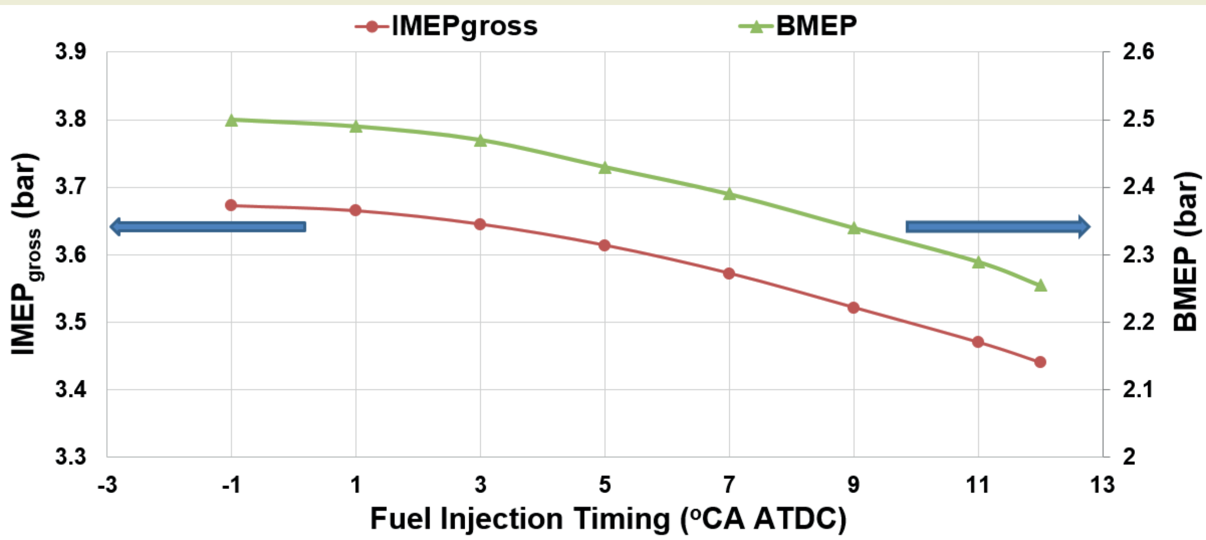

Figure 4. Effect of late fuel injection timing on $IMEP_{gross}$ and BMEP.

in Figure 4. It is explicit that BMEP is inevitably reduced as fuel injection is controlled in delayed timings. Constant fuel injection is inadequate to produce the same $IMEP_{gross}$ due to ineffective combustion. Lower $IMEP_{gross}$ results in reduced BMEP at RFI mode as the amount of fuel injection is kept constant. More energy needs to be utilized to maintain engine BMEP constant at 2.5 bar, which requires extra fuel injection, as seen earlier in Figure 3.

After demonstrating the effect of RFI, impact of EEVC on engine performance is examined in the following plots. At first, similar to RFI mode, the effect of EEVC on exhaust temperature and fuel penalty is observed in Figure 5 below. Advancing EVC timing in a slight manner does not noticeably affect exhaust temperature. However, after a certain EVC timing (particularly after 0°CA ATDC), exhaust temperature begins to rise sharply. Moderate use of EEVC can boost exhaust temperature as high as 230°C. Moreover, as EVC timing is advanced further than 15°CA BTDC, it is possible to sustain exhaust temperature above 250°C, which enables effective ETM and thus, effective EAT operation. Unlike RFI, EEVC technique in Figure 5 is able to keep the system in the effective ETM zone.

Similar to RFI technique, EEVC leads to fuel consumption penalty as shown in Figure 5. Slightly advanced EVC is not that problematic in terms of fuel penalty. However, as EVC timing is controlled significantly earlier than nominal

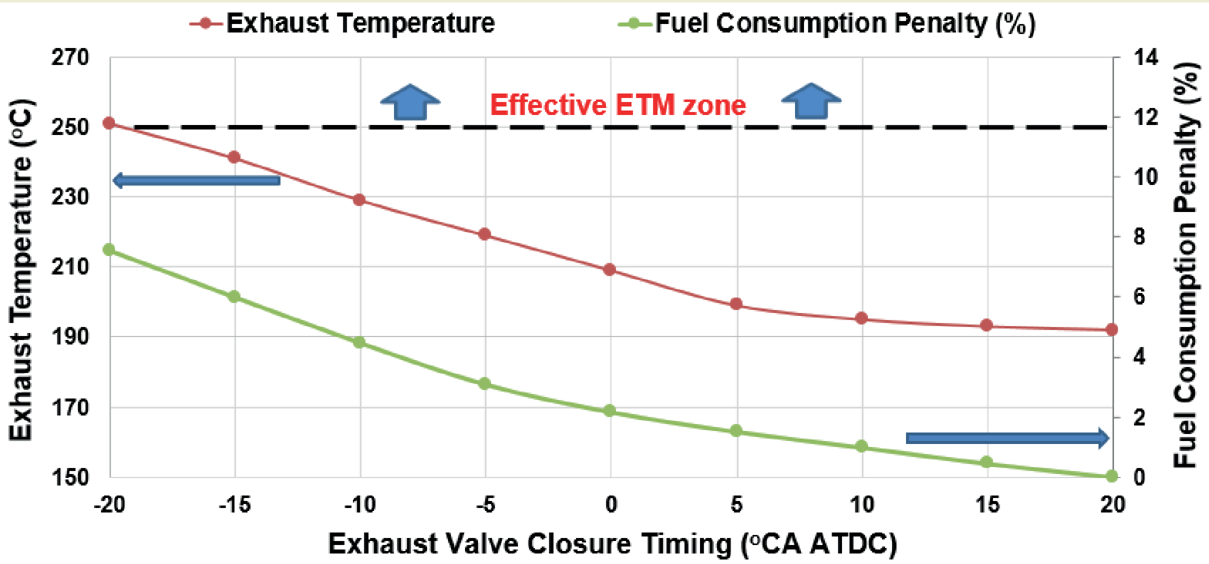

Figure 5. Effect of advanced EVC timing on exhaust temperature and fuel penalty.

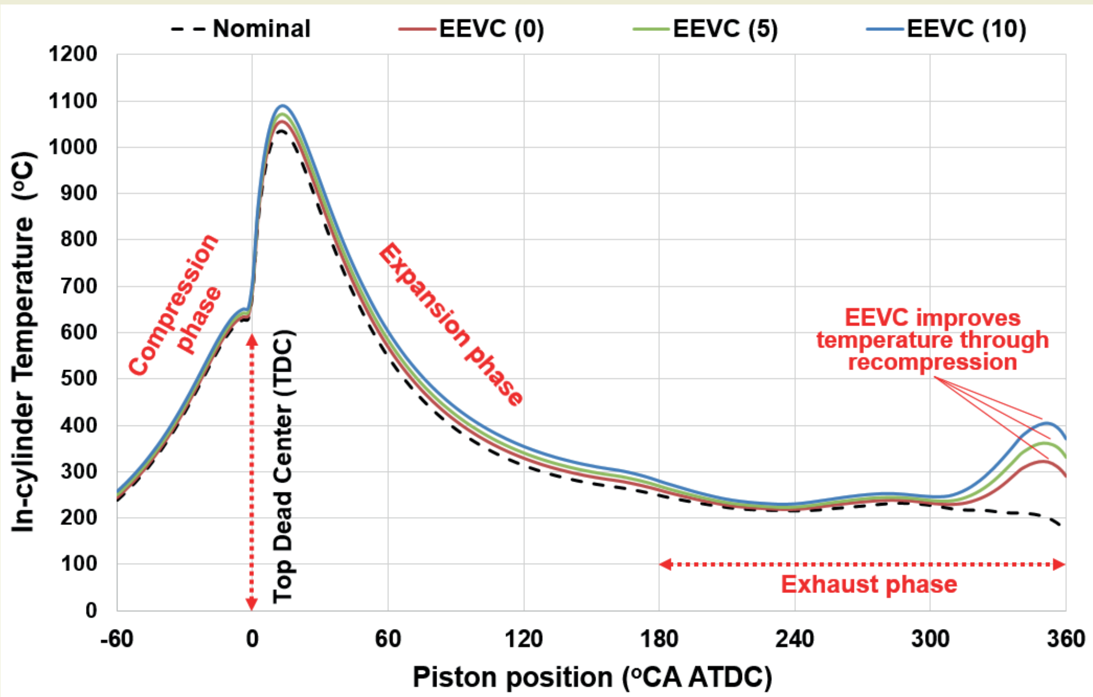

Figure 6. Effect of different EVC timings on in-cylinder temperature.

EVC timing, fuel penalty exceeds % 5 and can approach as high as % 8 in the system. Although there is an unavoidable increase in total fuel consumption in EEVC mode, the benefit of the method, namely the increase in exhaust unit temperature, is clearly visible in Figure 5. The potential of ETM improvement per fuel penalty rise in EEVC mode seems to be superior to the one achieved in RFI mode. In order to understand how EEVC is so effective at elevating exhaust temperature, the impact of EEVC on in-cylinder temperature is examined in Figure 6.

In-cylinder temperature behaves very differently for distinct EEVC modes – EEVC (0), EEVC (5) and EEVC (10) with EVC timing of 0°CA, 5°CA and 10°CA BTDC, respectively – in Figure 6. There is a particular variation in exhaust phase between nominal and EEVC modes. There is a noticeable recompression of exhaust gas in that period for EEVC cases, which is certainly not valid for nominal cases. As seen in Figure 6, there is a sudden rise in in-cylinder temperature in EEVC modes, which occurs due to early exhaust closure and compression of the in-cylinder gas. That recompression process mainly increases the pumping loss in the system and thus, leads to fuel penalty in Figure 5. In fact, fuel penalty is not the only negative effect of EEVC technique. Exhaust flow rate is reduced to low levels due to early shutoff of exhaust valves, as illustrated in Figure 7. Despite that considerable decrease in exhaust flow rate, rise in exhaust temperature is steadily improved through lowered air to fuel ratio (AFR), as seen in Figure 8.

Nominal exhaust flow rate (EVC at 20°CA ATDC) is maintained above 4.5 kg/min in Figure 7. However, particularly for moderate and extreme use of EEVC, exhaust flow rate drops down close to 3.5 kg/min, which is relatively low compared to nominal condition. As EVC is aggressively advanced, volumetric efficiency decreases close to % 70, which is considerable as it is almost % 25 lower than that obtained in nominal mode. That dramatic reduction in volumetric efficiency causes AFR to decrease

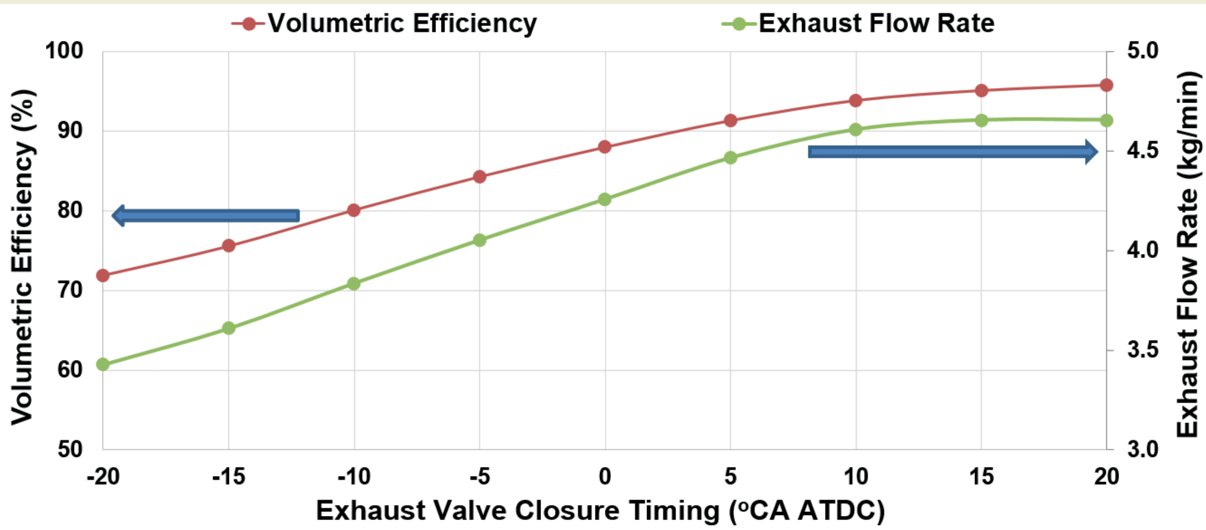

Figure 7. Effect of different EVC timings on volumetric efficiency and exhaust flow rate.

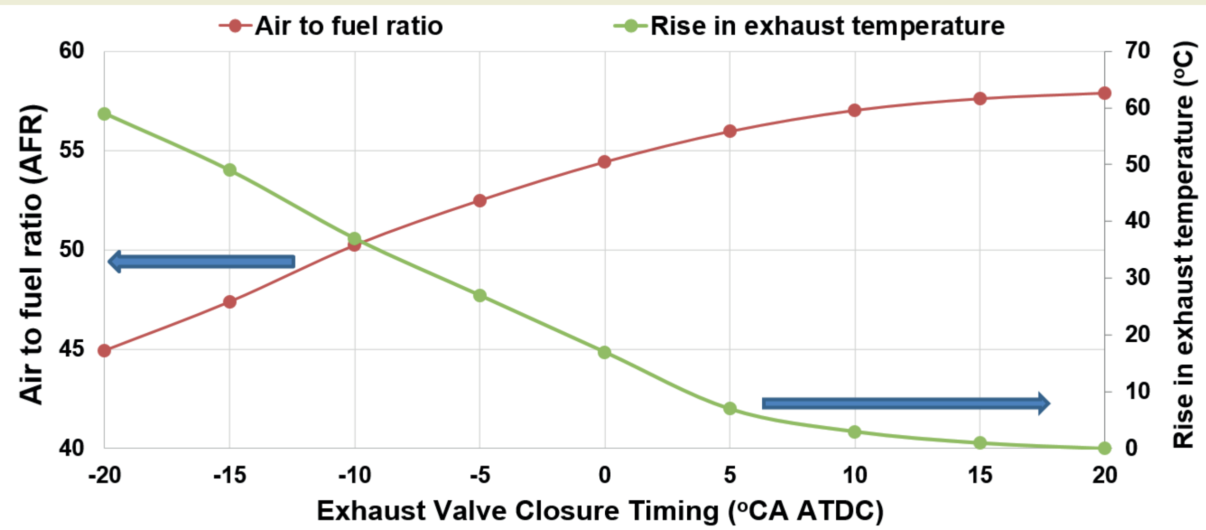

Figure 8. Effect of different EVC timings on AFR and rise in exhaust temperature.

as low as 45 and exhaust temperature improvement to be as high as 60°C in Figure 8. However, it is not that helpful to improve EAT warm up since heat up process generally needs high exhaust flow rate and thus, high in-cylinder airflow, which is not available in EEVC mode.

As seen earlier, RFI causes an undesirable fuel penalty with moderate rise in exhaust temperature in Figure 3. Moreover, EEVC elevates engine-out temperature with a notable decrease in exhaust flow rate in Figure 7. In order to elevate exhaust temperature with high exhaust flow rate, RFI and EEVC are combined as EEVC+RFI in the system, as presented previously in Table 3. The effect of different combinations of EEVC+RFI modes on exhaust temperature and BSFC are shown in Figure 9.

RFI alone and EEVC alone modes are placed in Figure 9 to compare them with the EEVC+RFI combined modes. As exhaust temperature is not the only parameter to assess the heat transfer rates to the EAT unit, the effect of those different combinations on exhaust flow rate is examined in Figure 10 as well. Considering the evident reduction in

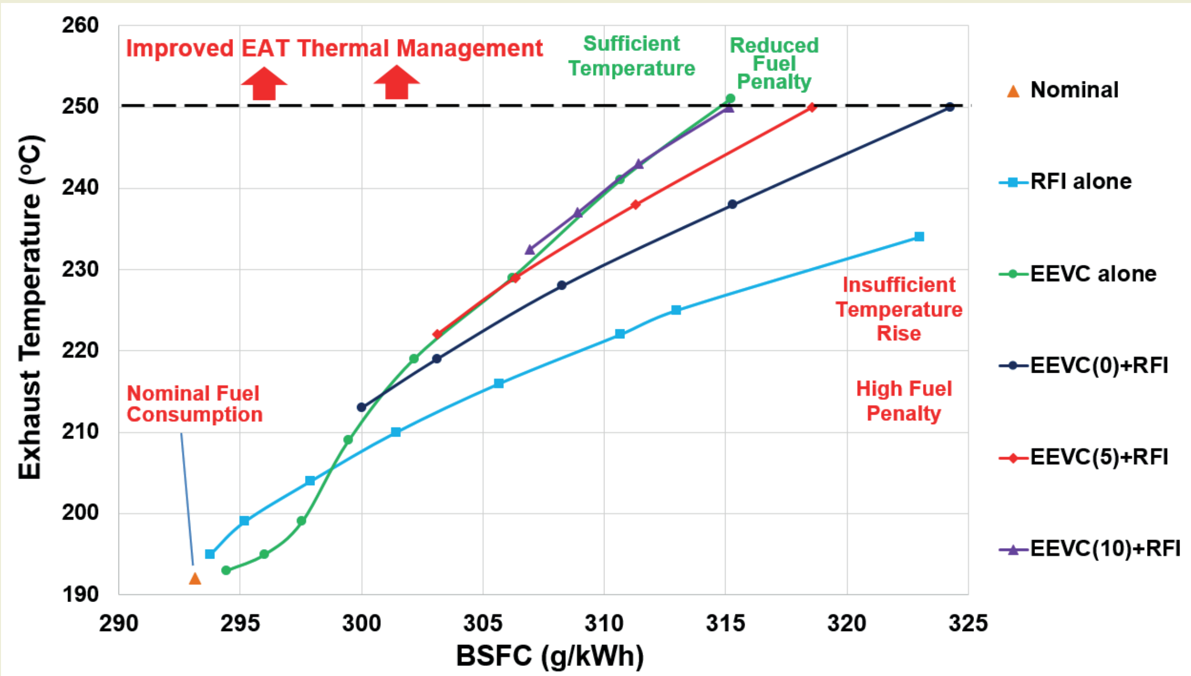

Figure 9. Effect of EEVC, RFI and EEVC+RFI modes on exhaust temperature and BSFC.

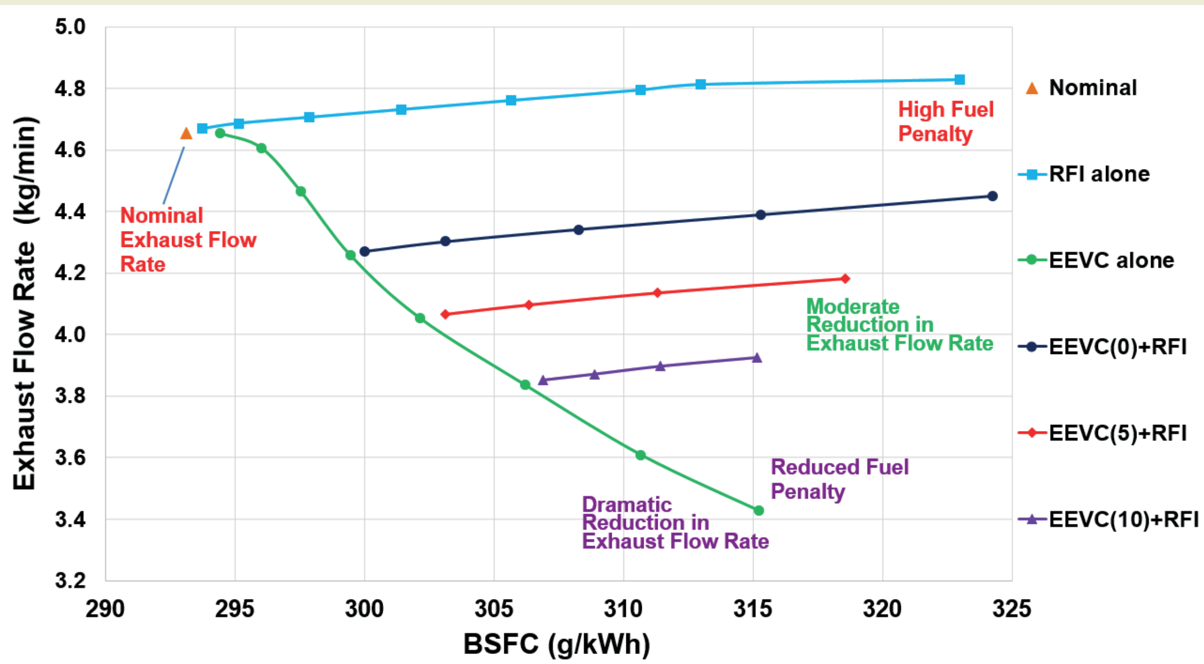

Figure 10. Effect of EEVC, RFI and EEVC+RFI modes on exhaust flow rate and BSFC.

exhaust flow rate in EEVC mode in Figure 7, evaluating only the exhaust temperature rise in a system is mostly insufficient to estimate its EAT improvement potential.

The most dramatic reduction in engine-out exhaust flow rate is observed in EEVC alone mode in Figure 10. This is because it has the most advanced EVC timing (20°CA BTDC) among all techniques. At this extreme position, exhaust port is sealed so early that exhaust flow rate is limited to close to 3.4 kg/min, which is dramatically below the nominal exhaust flow rate of close to 4.7 kg/min. As the closure timing is controlled at moderate levels, similar to EEVC (10) and EEVC (5) modes, exhaust flow rate begins to approach the level achieved in nominal mode. In RFI mode, exhaust flow rate increases compared to nominal mode since RFI, unlike EEVC-based methods, has a negligible effect on volumetric efficiency. It also causes the system to consume higher amount of fuel, resulting in the highest exhaust rate among all techniques.

The warm up process of the EAT unit can be best analyzed through considering the effect of both exhaust temperature ($T_{exhaust}$) and exhaust mass flow rate ($\dot{m}_{exhaust}$). Therefore, heat transfer rates $(\dot{Q})$ to the EAT unit are calculated using the equation (1) below [30]:

$$\dot{Q} = C(\dot{m}_{exhaust})^{\frac{4}{5}}\,(T_{exhaust} - T_{EAT\ catalyst\ bed}) \quad (1)$$

The $\dot{Q}$ rates are calculated at 1200 RPM and 2.5 bar BMEP for all methods. Then they are normalized by dividing all the values by the one achieved in nominal mode at 0°C EAT temperature. Those normalized heat transfer rates at different modes are indicated in Figure 11.

Nominal mode is seen to be the least effective method in Figure 11. The fact that exhaust temperature is too low to maintain EAT unit over 250°C is considered to be the main reason for this ineffectiveness. Since the magnitude of heat transfer (the temperature to which the EAT unit to be heated up) is mostly determined by exhaust temperature, nominal mode is predicted to be the worst case among all techniques as it has the lowest exhaust temperature (195°C). High exhaust flow rate in this mode affects EAT cool off process negatively as well.

RFI technique rises both exhaust temperature & exhaust flow rate and thus, it is the most effective method, particularly between -50°C and 50°C EAT temperature. However, exhaust temperature is limited to 225°C in that mode, and as EAT remains above 50°C, its effectiveness deteriorates. It is more advantageous to use EEVC+RFI techniques in Figure 11 when $T_{EAT\ unit}$ exceeds 50°C. This is because not only is it possible to sustain EAT unit temperature at 250°C in those techniques, but also the required fuel penalty can be reduced to as low as % 7.5, which is a significant benefit compared to RFI alone mode. The highest $\dot{Q}$ improvement (% 111) is achieved in EEVC(5) + RFI combined mode with % 8.6 fuel penalty, which demonstrates the benefit of combination and reasonable use of each method when the only objective is to maintain effective, fuel efficient after-treatment in the system. However, using only EEVC (5) + RFI may not be the fastest way to achieve active EAT operation in Figure 11. Considering the potential of RFI at cold EAT temperatures (particularly below 50°C), a better option for rapid EAT warm up may be to start with RFI alone and then continue the warm up process with EEVC (5) + RFI technique as $T_{EAT\ unit}$ exceeds 50°C in the system. Instead of a single strategy, it seems more attractive to apply different strategies during EAT get-hot process in Figure 11.

EEVC alone mode is found to be not that effective to accelerate the EAT get-warm process in Figure 11 although it can noticeably rise exhaust temperature above 250°C.

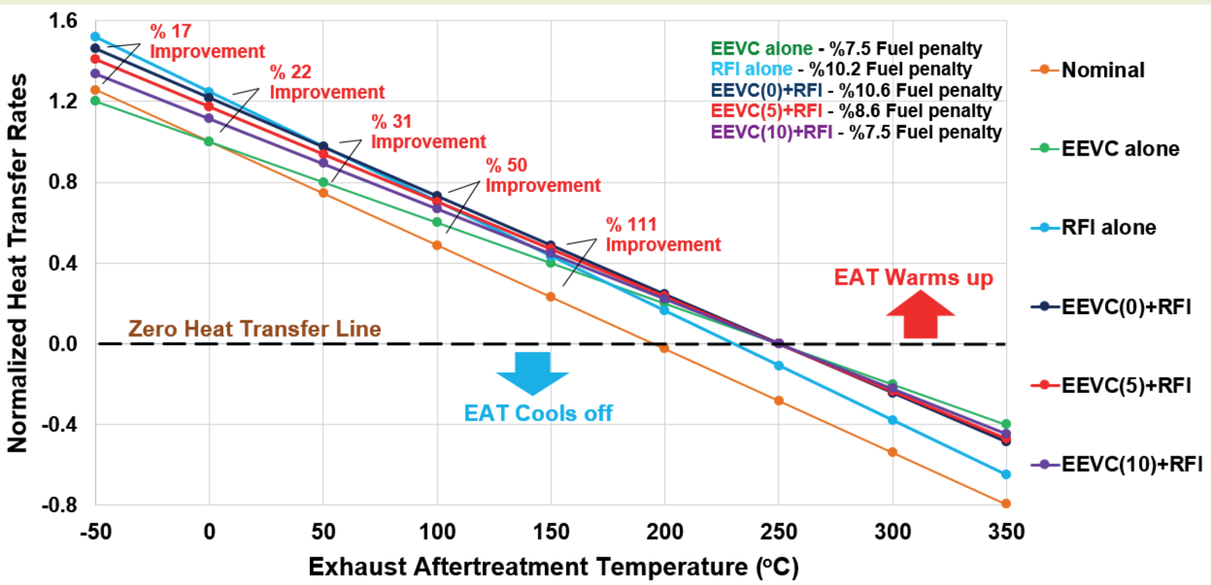

Figure 11. Change of heat transfer rates in EEVC, RFI and EEVC+RFI modes at 1200 RPM and 2.5 bar BMEP.

This is because EEVC brings down exhaust flow rate considerably (more than % 25) when it is aggressively used, as shown earlier in Figure 7. However, when $T_{EAT\ unit}$ is above 250°C, EEVC alone mode is found to be highly helpful to improve negative heat transfer rates due to low exhaust flow rates. Unlike RFI alone and nominal modes, those enhanced negative heat transfer rates in EEVC mode can slow down the EAT cool off process and can keep EAT unit above 250°C for longer periods of time. The requirement of only % 7.5 fuel penalty, which is relatively lower compared to other modes, is another important advantage of this technique during EAT stay-warm period in Figure 11.

4. Conclusion

This work concentrates on the improvement of EAT thermal management via use of RFI and EEVC. Firstly, the impact of those techniques is examined individually. It is seen that RFI can boost exhaust temperature in a moderate manner (from 195°C to 225°C) with a high fuel penalty (above % 10). Exhaust flow rate is not affected negatively in RFI mode. Unlike RFI, EEVC can rise exhaust temperature above 250°C with a relatively low fuel penalty (below % 8), which is advantageous. However, EEVC alone leads to a significant decrease (close to % 25) in exhaust flow rate, which affects EAT warm up negatively.

Considering the benefits of each mode, RFI and EEVC are simultaneously applied in the system as EEVC + RFI combined mode. The potential of different EEVC + RFI combined modes on the improvement of exhaust temperature, exhaust flow rate and EAT warm up is explicitly examined. It is observed that EEVC + RFI combined mode can increase exhaust temperature above 250°C with improved fuel penalty compared to RFI alone mode and can keep exhaust flow rate at higher levels compared to EEVC alone mode. Proper combination of RFI and EEVC has the capacity to achieve % 111 heat transfer rate improvement in comparison to nominal mode with a fuel penalty of % 8.6, which neither EEVC alone nor RFI alone method can achieve even with higher fuel penalty (above % 10). EEVC + RFI combined mode is also superior to RFI alone mode since it can improve EAT cool off process through reduced negative heat transfer rates to the EAT unit.

EEVC + RFI combined mode still causes undesirable fuel penalty in the system. Therefore, for fuel-efficient EAT warm up in diesel engine systems, other thermal management methods such as late intake valve closure or post-fuel injection can also be implemented in future studies to keep fuel penalty at feasible levels.

5. Nomenclature

ABDC After bottom dead center
AFR Air to fuel ratio
ATDC After top dead center
BBDC Before bottom dead center
BMEP Brake mean effective pressure, bar
BSFC Brake specific fuel consumption, g/kWh
BTDC Before top dead center
CA Crank angle, degree
DOC Diesel oxidation catalyst
EAT Exhaust after-treatment
EEVC Early exhaust valve closure
ETM Exhaust thermal management
EVC Exhaust valve closure
FIT Fuel injection timing
$IMEP_{gross}$ Gross indicated mean effective pressure, bar
LNT Lean NOx Trap
NOx Nitrogen oxide
RFI Retarded fuel injection
RPM Revolution per minute
SCR Selective catalytic reduction
SOI Start of injection timing, degree
TDC Top dead center
VVT Variable valve timing

Acknowledgement

I would like to sincerely thank Lotus Engineering Company for letting me use Lotus Engine Simulation software in this work.

Research Ethics

Ethical approval not required.

Author Contributions

The author accept full responsibility for the content of this article and have approved its submission.

Competing Interests

The author declare that there are no competing interests.

Research Funding

Not reported.

Data Availability

Not applicable.

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