Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Quantitative estimation of the impact of ash accumulation on diesel particulate filter related fuel penalty for a typical modern on-road heavyduty diesel engine



AppliedEnergy

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HIGHLIGHTS

- DPF model considering ash effects is built and validated.
- Quantitative analysis on the impact of ash on DPF related engine fuel penalty.
- DPF ash induced fuel penalty typically ranges from 0.02% to 0.42%.
- DPF lifetime fuel penalty can be reduced by ash cleaning interval optimization.
- Fuel saving potential of DPF ash management typically ranges from 0.22% to 0.69%.

ARTICLE INFO

Keywords: Diesel engine PM DPF Ash Fuel penalty Quantitative estimation

ABSTRACT

Fuel saving and emission reduction are big challenges in the development of diesel engines. Diesel particulate filters (DPF) can effectively reduce particulate matter (PM) emissions of diesel engines but negatively affect the engine fuel economy. Some previous studies have been conducted to investigate the effects of DPFs on engine fuel economy, however, nearly all previous studies have neglected the impact of ash accumulation on DPF related fuel penalty. This work aims to quantitatively estimate the impact of ash accumulation on DPF related fuel penalty for a typical modern on-road heavy-duty diesel engine. For this purpose, a one-dimensional full-size DPF model considering ash effects was built and validated in this work, and an engine bench test was conducted to evaluate the effects of exhaust backpressure on engine fuel consumption. An estimation method for the quantitative evaluation of the impact of ash accumulation on DPF related engine fuel penalty was proposed based on the model and experimental data. Subsequently, the impact of ash accumulation on DPF lifetime fuel penalty as well as the potential of fuel saving by DPF ash management for a typical modern on-road heavy-duty diesel engine were quantitatively analyzed. In addition, the effects of engine-out PM emission concentration and DPF maximum soot loading prior to regeneration on the impact of ash accumulation on DPF lifetime fuel penalty and the fuel saving potential of DPF ash management are investigated with the estimation method. The results showed that the DPF ash induced fuel penalty ranged from 0.02% to 0.42% for the typical modern on-road heavy-duty diesel engine studied in this work, and the DPF lifetime fuel penalty could be reduced by optimizing the DPF ash cleaning interval. The fuel saving potential of DPF ash management ranged from 0.22% to 0.69% for all the cases studied in this work, which has the similar magnitude to some specific individual applications such as engine friction reduction, lowering accessory losses, or pumping optimization. Both the DPF ash induced fuel penalty and the fuel saving potential of DPF ash management are increasing with the rise of engine-out PM emission concentration no matter the DPF control strategy is implemented without or with ash correction, while the DPF maximum soot loading prior to regeneration showed little effects on the ash induced fuel penalty and the fuel saving potential of DPF ash management.

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https://doi.org/10.1016/j.apenergy.2018.08.071

Received 17 April 2018; Received in revised form 7 August 2018; Accepted 15 August 2018 0306-2619/@ 2018 Published by Elsevier Ltd.

| Abbreviations p_1 pressure in the inder channel (Pa)BMEP BMEP BFCbrake specific fuel consumption λp_0 pressure loss of the shark clace (Pa)BMEC BSCbrake specific fuel consumption λp_0 pressure loss of the shark clace (Pa)C C C carbon monoxide λp_0 pressure loss or the filter unlet (Pa)C C carbon monoxide λp_0 pressure loss or the filter unlet (Pa)CC C carbon monoxide λp_0 pressure loss or the filter unlet (Pa)CC C carbon divide λp_0 pressure loss or the DPF inlet plug (Pa)DOC DOC C deal oxidation catalyst $\lambda p_{0,0}$ pressure loss or the sap plug and DPF outlet plug pressure loss of the soot cake (Pa)DPF DFC FUCfilter outlet (Pa) pressure loss of the soot cake (Pa)DPF DFC DFC C Furopean transient cycle λp_0 pressure loss of the soot cake (Pa)DPG DO2 O O O NO2 a nitric oxideRTF regeneration fuel penalty (%) regeneration fuel penalty (%) restrict lost of the denominator term of f_{CO} (-) rotal number of reaction rate of reaction (kmO/(M=N))NO2 a oxides of nitrogen O O O O O O Q a oxides of nitrogenRTF regeneration fuel penalty (%) regeneration fuel penalty (%)NO3 a nitrogen dioxideRTF regeneration fuel penalty (%) regeneration fuel penalty (%) r | Nomenc | lature | \overrightarrow{n} | normal vector to the surface of the DPF solid part (-) |
|---|---------------|---|----------------------|--|
| BMEP BMEPbrake mean effective pressure brake specific fuel consumption P_{det} A_{fec} A_{fec} A_{fec} A_{fec} A_{fec} pressure loss of the ash cake (Pa) A_{fec} pressure loss of the ash cake (Pa) A_{fec} pressure loss of the ash cake (Pa) A_{fec} pressure loss at the filter identity (Pa) A_{fec} pressure loss at the filter identity (Pa) A_{fec} pressure loss of the solid catalyst A_{fec} pressure loss of the solid catalyst A_{fec} A_{fec} pressure loss of the solid catalyst A_{fec} A_{fec} pressure loss of the solid catalyst A_{fec} A_{fec} A_{fec} A_{fec} A_{fec} A_{fec} A_{fec} | | | p_1 | pressure in the inlet channel (Pa) |
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| BSFCbrake specific fuel consumption Δ_{DTPT}^{P} DPF overall pressure dos over the effective filter length (Pa)Ccarbon monoxide Δ_{Ref}^{P} pressure loss over the effective filter length (Pa)CO2carbon monoxide Δ_{Ref}^{P} pressure loss over the effective filter length (Pa)CO2carbon monoxide Δ_{Ref}^{P} pressure loss over the DFF inlet plug (Pa)CO2carbon monoxide Δ_{Ref}^{P} pressure loss over the ash plug and DFF outlet plug.DCCdesel particulate filter Δ_{Ref}^{P} pressure loss of the soot cabe(Pa)DFCEuropean transient cycle Δ_{Ref}^{P} pressure loss of the soot cabe(Pa)ND2nitrice acide R universal gas constant (LA/(kmokK))ND2nitrice acide R universal gas constant (LA/(kmokK))NO2nitrogen dioxide R universal gas constant (LA/(kmokK))NO2nitrogen dioxide R universal gas constant (LA/(kmokK))NO2nitrogen dioxide R veta evaraged regeneration fuel penalty (%)O3original engine manufacturer β reaction rate of reaction i (kmol/(m ³ s))PMparticulate mater s total number of species (-)S solid state S_2 wet perimeter of the outlet channel (m)SVspace velocity T_q exhaust gas temperature (K)UHSCworld harmonized stationary cycle T_q RFP pecearation fuel penalty (%) T_q RFP backpressure fuel penalty (%) T_q < | | | Pout | pressure at the filter outlet (Pa) |
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| $ \begin{array}{cccc} CO & \operatorname{carbon monoxide} & \Delta P_{real} & \operatorname{pressure loss at the filter inlet (Pa) \\ CO_2 & \operatorname{carbon dioxide} & \Delta P_{real} & \operatorname{pressure loss over the filter outlet (Pa) \\ DCC & \operatorname{diesel oxidation catalyst} & \Delta P_{pleq,rinl} & \operatorname{pressure loss over the ash plug and DPF outlet plug \\ DDC & Department of Energy & \Delta P_{real} & \operatorname{pressure loss over the ash plug and DPF outlet plug \\ DPF & \operatorname{diesel oxidation catalyst} & \Delta P_{pleq,rinl} & \operatorname{pressure loss over the ash plug and DPF outlet plug \\ DPF & \operatorname{diesel oxide filter} & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \Delta P_{de} & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \Delta $ | BSFC | brake specific fuel consumption | Δp_{DPF} | DPF overall pressure drop (Pa) |
| $ \begin{array}{cccc} CO & \operatorname{carbon monoxide} & \Delta P_{real} & \operatorname{pressure loss at the filter inlet (Pa) \\ CO_2 & \operatorname{carbon dioxide} & \Delta P_{real} & \operatorname{pressure loss over the filter outlet (Pa) \\ DCC & \operatorname{diesel oxidation catalyst} & \Delta P_{pleq,rinl} & \operatorname{pressure loss over the ash plug and DPF outlet plug \\ DDC & Department of Energy & \Delta P_{real} & \operatorname{pressure loss over the ash plug and DPF outlet plug \\ DPF & \operatorname{diesel oxidation catalyst} & \Delta P_{pleq,rinl} & \operatorname{pressure loss over the ash plug and DPF outlet plug \\ DPF & \operatorname{diesel oxide filter} & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \Delta P_{de} & \Delta P_{de} & \operatorname{pressure loss of the soot cake (Pa) & \Delta P_{de} & \Delta $ | С | carbon | | pressure loss over the effective filter length (Pa) |
| $\begin{array}{cccc} CO_2 & \operatorname{carbon dioxide} & \Delta T_{adv} & \operatorname{pressure loss over the DPF inlet plug (Pa) \\ \Delta P_{plag,out} & \operatorname{pressure loss over the DPF inlet plug (Pa) \\ \Delta P_{plag,out} & \operatorname{pressure loss over the DPF inlet plug (Pa) \\ DOC & \operatorname{diesel particulate filter & \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{pressure loss of the soot cake (Pa) \\ \Delta P_{adv} & \operatorname{presoure cand tech canae (Pa) \\ \Delta P_{adv} & pressure c$ | CO | carbon monoxide | | pressure loss at the filter inlet (Pa) |
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| $ \begin{array}{lll} c_{p,s} \\ c_{p,s} \\ c_{p,s} \\ d_{p,s} \\ c_{p,s} \\ d_{p,s} \\ c_{p,s} \\ c_{p,s$ | | | | |
| | | | $v_{i,k}$ | |
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| F_2 friction coefficient in the outlet channel (-) $w_{g,k}$ mass fraction of the species k (kg/kg)FCengine fuel consumption rate (kg/h) y_g mole fraction (mol/mol) f_{CO} temperature dependence factor (-)Greek lettersGSAgeometry surface area for DPF inlet and outlet channels (m ² /m ³)Greek letters | E_i | activation energy of reaction i (kJ/kmol) | v_{w1} | wall velocity in the inlet channel (m/s) |
| FC engine fuel consumption rate (kg/h) y_g mole fraction (mol/mol) f_{CO} temperature dependence factor (-) geometry surface area for DPF inlet and outlet channels Greek letters (m^2/m^3) mole fraction (mol/mol) fraction (mol/mol) | F_1 | friction coefficient in the inlet channel (-) | v_{w2} | wall velocity in the outlet channel (m/s) |
| f_{CO} temperature dependence factor (-) GSA geometry surface area for DPF inlet and outlet channels Greek letters (m^2/m^3) | F_2 | | $w_{g,k}$ | mass fraction of the species k (kg/kg) |
| f_{CO} temperature dependence factor (-) GSA geometry surface area for DPF inlet and outlet channels Greek letters (m^2/m^3) | FC | engine fuel consumption rate (kg/h) | | mole fraction (mol/mol) |
| GSA geometry surface area for DPF inlet and outlet channels Greek letters (m^2/m^3) | f_{CO} | temperature dependence factor (-) | 8 | |
| (m^2/m^3) | | geometry surface area for DPF inlet and outlet channels | Greek lett | ers |
| a second s | | | | |
| H_u lower heating value of the diesel fuel (kJ/kg) α ash content of the lubricant oil (%) | H_{ν} | lower heating value of the diesel fuel (kJ/kg) | α | ash content of the lubricant oil (%) |
| K anisotropic heat conduction matrix (W/(m·K)) δ_{ac} height of the ash cake (m) | | | δ_{ac} | |
| k_{ac} permeability of the ash cake (m ²) δ_{sc} height of the soot cake (m) | | - | | - |
| k_{ac} exponential factor of the denominator term of f_{CO} (–) δ_{sd} height of the soot dente (m) | | | | - |
| k_f gas-solid heat transfer coefficient (W/(m ² ·K)) δ_w thickness of the filter wall (m) | | | | |
| k_i Arrhenius frequency factor of reaction <i>i</i> (variable) μ gas viscosity (Pa·s) | | | | |
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| 1 in the set of (1) in the set (1) | | | | |
| l length of the DDE inlet /outlet nive (m) | | | | |
| in anging orthoust mass flow rate (ligh) | | | | |
| $\dot{m}_{exhaust}$ engine exhaust mass flow rate (kg/h) φ DPF channel shape factor (-) | | | | - |
| \dot{m}_{fuel} fuel injection rate (kg/h) ζ_{inl} pressure loss coefficient at the filter inlet (-) | • | | | |
| M_j molar mass of the species <i>j</i> (kg/kmol) ζ_{out} pressure loss coefficient at the filter outlet (–) M_k molar mass of the species <i>k</i> (kg/kmol) | 5 | | Sout | pressure loss coefficient at the filter outlet (-) |
| M_k molar mass of the species k (kg/kmol) | IVIK | motar mass of the species k (kg/kmol) | | |

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