Institution: City, University of London (CUL)

Unit of Assessment: Engineering

Title of case study: Design of high-pressure durable fuel injectors and viscoelastic fuel additives

Period when the underpinning research was undertaken:
2012-2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Professor Manolis Gavaises	Professor	2001-present
Dr Foivos (Phoivos) Koukouvinis	Lecturer	2012-present
Dr Ioannis Karathanassis	Lecturer	2015-present

Period when the claimed impact occurred: 2014-present

Is this case study continued from a case study submitted in 2014? Y

1. Summary of the impact (indicative maximum 100 words)

Research carried out at City, University of London (CUL) since 2012, led to development of: (i) optical, laser and X-ray diagnostic methods for cavitating flows and (ii) relevant CFD models that consider both real-fluid thermodynamics closure and non-Newtonian rheological effects induced by additives. Using these models as design tools in industrial practice resulted in significant economic and environmental impact: Caterpillar Engines (US)/Perkins Engines (UK) achieved: (a) £4.5M savings per year leveraged from commercial software tools and a non-trivial contribution to their £150B sales over the past 10 years, and (b) a considerable contribution to the 1.5M tones/year of CO_2 reduction from sold engines. Lubrizol Ltd (UK) achieved: (a) 10% increase of sales (£3.2M per year) of fuel additive and £2M per year of polymeric additives for hydraulic fluids and (b) 3-8% improvement in power savings with corresponding 0.5M tones/year of CO_2 savings.

2. Underpinning research (indicative maximum 500 words)

Diesel engines contribute to ~17% of global CO_2 emissions annually. During the last two decades, combined efforts from industries, academic and research institutions, governments and policy makers have demanded and gradually implemented technologies that lead to more than 90% reduction of pollutant emissions and significant increase in engine thermodynamic efficiency. It is estimated **[3.1]** that the relevant energy savings from the improved combustion of such fuels is similar to the energy produced from all renewable energy sources together, over this period of time. Research at City, University of London (CUL) led by Prof Gavaises, Dr Koukouvinis and Dr Karathanassis has focused on two pillars relevant to the development of high pressure fuel systems for such engines, which is a core technology that enabled these improvements: (i) development of optical, laser and X-ray diagnostic methods for cavitating flows; (ii) development of relevant CFD models that consider both real-fluid thermodynamics closure and non-Newtonian rheological effects induced by the presence of additives dispersed in fuels and hydraulic fluids. The combined £4.5M research of 9 research grants (**G**), listed below, has funded 12 awarded PhD Theses and 27 employment-years of 8 post-doctoral research fellows at CUL. The relevant research findings have been published in 63 peer-reviewed scientific journals.

Grants **G1**, **G2** and **G3** focused on the modelling and experimental validation of fundamental processes relevant to bubble dynamics and cavitation erosion **[3.2]**. Moreover, this is the first work to include real-fluid thermodynamics closure models able to predict the large variation of fuel physical and transport properties as function of pressure and temperature. This allowed predictions of fuel heating/cooling effects in cavitating flows in fuel injectors during extreme fuel pressurisation. A novel extension of this research has been performed in grant **G4** and considered the development of a computational methodology for modelling cavitation erosion in high pressure fuel injectors and published jointly with Caterpillar **[3.3]**. Further developments, part of grant **G5**, have considered, for the first time, simulation of cavitation in diesel injectors at fuel pressures as high as 450MPa **[3.4]**. Transfer of these models to industrial practice took place in grant **G6**.

In a parallel and complementary activity of grants **G7** and **G8**, the physical mechanism through which detergent quaternary ammonium SAlts (*QAS*) additives affect the rheological characteristics of cavitating high pressure Diesel fuel injectors has been identified **[3.5]**. The relevant publication reports jointly with Lubrizol Ltd experimental and computational results including high speed X-ray phase contrast images performed at the ANL Advanced Photon Source and neutron scattering measurements obtained at Rutherford Appleton Laboratory. The findings verified viscoelastic micelle formation, inducing viscoelasticity behaviour on the flowing diesel fuel. Finally, as part of grant **G9**, the performance effectiveness of two non-Newtonian oil compounds, containing poly(alkylmethacrylate) (PMA) and poly(ethylene-co-propylene) (OCP) polymers, respectively, have been comparatively investigated against a base, monograde viscous hydraulic oil **[3.6]**; these are utilised in geometrically-complex hydraulic circuits of earth-moving machines. The results have demonstrated that viscoelastic effects setting is due to the OCP additives tend to reduce the magnitude of the secondary flow pattern, by as much as 15% on average compared to the base liquid. That resulted to a significant, up to 8%, reduction in pressure losses during the flow of the hydraulic fluids.

3. References to the research (indicative maximum of six references)

3.1 ExxonMobil, *The Outlook for Energy: A View to 2040*, 2014
3.2 G. Strotos, P. Koukouvinis, A. Theodorakakos, **M. Gavaises**, G. Bergeles 'Transient heating effects in high pressure Diesel injector nozzles', International Journal of Heat and Fluid Flow, Volume 51, Pages 257-267, 2015
3.3 P. Koukouvinis, M. Gavaises, J. Li, L. Wang 'Large Eddy Simulation of Diesel Injector including cavitation effects and correlation to erosion damage', *FUEL*, Volume 175, Pages 26–39, 2016.
3.4 A. Vidal, K. Kolovos, P. **Koukouvinis, M. Gavaises**, M. Gold and R. Pearson 'Preferential cavitation and friction-induced heating of multi-component Diesel fuel surrogates up to 450MPa', *International Journal Heat and Mass Transfer*, Volume 166, No 120744, 2021
3.5 H. Naseri, K. Trickett. **I.K. Karathanassis, P. Koukouvinis, M. Gavaises**, R. Barbour, M. Santini, J. Wang 'Turbulence and Cavitation Suppression by Quaternary Ammonium Salt Additives', *Scientific Reports* 8, Article number: 7636, 2018.
3.6 I.K. Karathanassis, E. Pashkovski, M. Heidari-Koochi, H. Jadidbonab, T. Smith, **M. Gavaises**, C. Bruecker 'Non-Newtonian flow of highly-viscous oils in hydraulic components', *Journal of Non-Newtonian Fluid Mechanics*, Volume 275, 104221, 2020

The research underpinning the impact case has been performed as part of the following grants (**G**) awarded to City, University of London:

G1. 2012-2016 The Lloyds Register Foundation 'The International Institute of Cavitation Research'. *£835,000*
G2. 2013-2017, EU-FP7 Industry Academia Partnership and Pathways programme 'Simulation of cavitation and erosion in fuel injection systems of medium/ heavy duty Diesel engines at injection pressures reaching 3000bar (FuelSystem3000)', Perkins Engines (UK) and Caterpillar Fuel Systems (US) as partners. G.A. PIAP-2012-324313. *€1,206,231*
G3. 2014-2017 EU-FP7 MC-IOF 'Cavitation bubble cloud dynamics and surface erosion in high pressure fuel systems for medium/heavy duty Diesel engines (CavFuelSystem)', G.A. PIEF-2012-329286. Project supported by Caterpillar Fuel Systems, US. *€374,000*
G4. 2015-2019, H2020 MSCA-ETN, Development and experimental validation of computational models for cavitating flow, surface erosion damage and material loss (CAFÉ), G.A. 642536. *€1,332,000*
G5. 2015-2019 H2020 MC-ETN 'Effect of 4500bar injection pressure and supercritical phase change of surrogate and real-world fuels enriched with additives and powering Diesel engines, on soot emissions reduction (IPPAD)'. G.A. 675528. Perkins Engines (UK), Caterpillar Fuel Systems

(US) as project partners. *€929,611*
G6. 2016-2020 Caterpillar Engines Grant to City, University of London. ‘Development of CAVFOAM simulation tool’. *£155,000*
G7. 2013-2016 EU-FP7 MC-IOF ‘Fuel Additives Effect on Fuel Injector Design (FAEFID)’ PIOF-2011-300410. Project supported by Lubrizol Ltd, UK. *€250,000*.
G8. 2013-2018 Lubrizol Ltd, UK, PhD support on ‘Effect of fuel additive on injector volumetric efficiency’. *£70,000*
G9. 2018-2019 Lubrizol Ltd UK. ‘Flow measurements in viscoelastic additives’. *£80,000*

4. Details of the impact (indicative maximum 750 words)

4a. Caterpillar
(i) Economic impact
Over the past 10 years, CUL and Caterpillar have worked jointly to develop, design and manufacture Diesel and dual-fuel power systems that meet all global emissions regulation standards. Much of these improvements have been derived by advancements in fuel injection technology and combustion system design. On average, fuel injection pressures have increased from 120MPa to 250MPa on their state-of-the-art engines. Heavy duty applications have demanding durability requirements. In addition to being robust to harsh environmental conditions, these engines must also last tens of thousands of hours of operation at high duty (load) factors. Higher injection pressures, while beneficial, also can result in injector damage via cavitation erosion. Caterpillar has worked with Prof Gavaises at CUL, for more than 15 years to develop, improve and apply simulation tools to design Caterpillar fuel injection systems. City University has led collaborative research projects to improve physical understanding and the fidelity of fuel injection simulations. As a member of these research collaborations, according to Caterpillar’s letter of support (5.1): *‘Caterpillar has thereby leveraged more than £4.5M of simulation tool improvement efforts, and applied these outcomes to develop both common rail and Mechanically actuated Electronically controlled Unit (MEUI) injection systems. While it is difficult to attribute specific sales numbers to the application of advanced fuel injector system technology, and even more so to the enabling simulation technology, it is clear that the contribution these tools made to the £150B of Caterpillar engine sales over the past 10 years, is non-trivial’*.

(ii) Environmental impact
By enabling such a large engine population in the field, the positive environmental impact of fuel system improvements over that period of time is significant. Particulate Matter (PM) from Caterpillar’s power dense engines have been reduced by more than 92% in that timeframe and fuel efficiency improved by 5-12% (depending on engine size and application). Furthermore, these higher injection pressures have driven faster combustion rates, significantly contributing to the afore-mentioned improvements in fuel consumption. According to Caterpillar (5.1): *‘Conservatively, over the past 10 years, more than 1.3 billion gallons of fuel have been saved for just Caterpillar-produced off-road machines, based on these engine-derived fuel efficiency benefits’.* This is equivalent to the CO_2 emissions of a 150,000 people UK-based city.

4b. Lubrizol
(i) Economic impact
Lubrizol has collaborated with CUL, in two projects that have had, and continue to have, a direct impact on Lubrizol’s business. The first project was the study of the origin of the so-called 'power gain additive’ for diesel engines. The additive was initially developed to keep diesel injectors clean and free from deposits, but also provided an unexpected boost in engine power for the same fuel pressure drop across the injector. Marketing this new state-of-the-art additive proved troublesome due to a lack of understanding of how it worked. Work at CUL, led by Prof Gavaises, explained how the Lubrizol additive induced viscoelastic effects in the fuel flow, leading to a reduction in cavitation inside fuel injector nozzles, therefore increasing fuel flow and causing a corresponding increase in engine power. This new understanding, became central to customer discussions around the performance virtues of this product, and opened unforeseen insight into how fuels flow through fuel injectors and impact engine outputs. According to Lubrizol (5.2): *‘Not only could be*

marketed as a deposit additive, but also an additive that genuinely provides power gain to the engine. The effects were profound, generating credibility at global OEMs and oil companies and sales were directly influenced by an estimated increase of 10%, (that corresponds to approximately £3.2 million revenue extra per year), which given the competitive landscape, is a remarkable success'.

The second profoundly successful project with Prof Gavaises' research group started in 2017, and similarly addressed a fluid dynamics problem that Lubrizol were unable to solve in-house. It came at the end of an ambitious program within Lubrizol to create a hydraulic fluid that provided energy savings of 3-8% (5.3). Like the engine power-gain project, customer scepticism was a major barrier to gaining sales. In less than six months, an experimentally-proven explanation was presented, based on well-established fluid dynamics and measurement science. According to Lubrizol (5.2): *'The impact in the industry has been huge. It can be estimated that even with a modest assumption City's contribution of £2 million of increased revenue are anticipated'.*

(ii) Environmental impact
A huge environmental impact of this project has been also realized in terms of energy savings. According to Lubrizol: *'the estimated CO_2 reduction at global scale over the next two years due to the use of this additive is estimated to be of the order of half million tones'*; this corresponds to the CO_2 emissions from a UK-based city of 50,000 inhabitants.

5. Sources to corroborate the impact (indicative maximum of 10 references)

5.1 Letter of support from Caterpillar

5.2 Letter of support from Lubrizol

5.3 Lubrizol Reference to the work done at City at about 2 minutes after the start
https://www.youtube.com/watch?v=XVRr7I_2wX4