Institution: City University London

Unit of Assessment: 15 General Engineering

Title of case study: Design of durable and more efficient fuel injectors now used by leading international engine manufacturers

1. Summary of the impact

Research undertaken at City University London has identified new ways to control vapour pockets, known as cavitation, that occur in diesel fuel injection nozzles. These computational methods have led to the design and manufacture of more durable and efficient fuel injectors that have been taken into serial production and are now used by major engine and component manufacturers such as Toyota, Caterpillar and Delphi. The prevention of erosion by cavitation and the greater efficiency of the fuel spray and combustion have generated economic benefits through a rise in sales of advanced injection systems and an extended life for engine components. Cleaner and more efficient engines in turn bring significant environmental benefits.

2. Underpinning research

Cavitation is described as the process of rapid growth and collapse of vapour pockets of resident nuclei in a liquid due to a reduction in the static pressure below the liquid vapour pressure. The occurrence of uncontrolled cavitation may result in surface erosion and damage of marine propellers, pumps, turbines, bearings and high pressure fuel injection equipment (FIE). FIE represents the key technology for reducing emissions in the cylinders of internal combustion engines (ICE).

Research into cavitation in FIE at City followed earlier work on ICE led by Professor Dinos Arcoumanis at Imperial College London. In 2000 the team led by Professor Arcoumanis relocated to City University London. In addition to Professor Arcoumanis (a member of academic staff since 2000), the team comprises Professor Manolis Gavaises and Professor Jamshid Nouri (members of academic staff since 2001), Professor John Carlton (a member of academic staff since 2009) and Dr Russel Lockett (a member of academic staff since 1999). The group led pioneering work exploring how experimental techniques (visualisation, laser diagnostics) can be applied to cavitation in optically accessible true-scale injectors as opposed to simplified test nozzles.[1, 2]

The team characterised flow regimes developing through fuel injectors, such as ‘string cavitation’. This is a new term introduced by the City group and now widely used. Measurements taken at City have also been the first to quantify cavitation using x-ray densitometry.[3] From this fundamental experimental research City has developed a new Computational Fluid Dynamics (CFD) cavitation model, [4, 5, 6] while an associated computational methodology has also been patented.[7] This allows characterisation of surface erosion caused by cavitation which enables industry to design more durable injectors.

City’s cavitation programme has been rewarded by sponsorship from 16 companies from the automotive, fuel injection and marine industries including BMW (2000-2005), Siemens Automotive (2002-2004), Yamaha (1999-2007), Nissan (2001-2003), Toyota (2005-2007) and Toyota Europe (2001-2009), MAN B&W (2003-2005), Delphi (2002-present) and Caterpillar/Perking (2005-2009) as well as receiving funding from TSB/EPSRC (2005-2008). Total funding across the period amounts to £7M. As a follow-up, Denso is currently supporting research at City on cavitation erosion and durability issues at a 3000bar injection pressure, which represents the next frontier in the field and is expected to come into production within the next three years.

The appointment in 2009 of Professor Gavaises to a sponsored Chair (the Delphi Professor in FIE Fluid Dynamics) demonstrates further industry commitment to the work. Professor Gavaises currently assists the Delphi Research & Development simulation/physical modelling group at Gillingham. Delphi holds more than 20% of the global FIE market and is ranked 1st among its competitors in developing countries such as India and China. In a parallel but relevant activity,

Professor Carlton, former Global Head of Lloyd's Register of Shipping, has been appointed as the first Professor of Marine Engineering at City and has expanded the activities of the group into cavitation in the marine sector.

In recognition of this combined expertise, in 2012 the team was awarded a grant from The Lloyd's Register Foundation to establish the first International Institute on Cavitation Research in partnership with Loughborough University and Delft University of Technology, The Netherlands (www.cavitation-institute.org). The Institute, which has its headquarters at City, acts as the umbrella for the coordination of a large number of research projects on cavitation worldwide. Currently the group is supported by an Industry Academia Partnership and Pathway EU programme, four Marie Curie Fellowships, one EPSRC grant and nine projects funded directly from industry (Shell, BP, Lubrizol, Afton, Denso, Wartsila, BAE Systems, Caterpillar and Delphi). These expand cavitation research in new areas such as automotive fuels and fuel additives technology and medical applications involving life-saving devices, for example cardiopulmonary bypass pumps, artificial hearts, and mechanical heart valves.

3. References to the research

Six publication outputs have been selected to represent the outcomes of the research along with one patent:

1. Arcoumanis C., Badami M., Flora H. & Gavaises M. (2000). Cavitation in real size multi-hole diesel injector nozzles, *SAE Technical Papers* 2000-01-1249, 10.4271/2000-01-1249
2. Andriotis A., Gavaises M. & Arcoumanis C. (2008). Vortex flow and Cavitation in Diesel Injector Nozzles, *J. Fluid Mech*., 610, 195-215 10.1017/S0022112008002668
3. Bauer D., Chaves H. & Arcoumanis C. (2012). Measurements of void fraction distribution in cavitating pipe flow using x-ray CT. *Meas. Sci. Technol.,* 23, 055302 10.1088/0957-0233/23/5/055302
4. Giannadakis E., Gavaises M. and Arcoumanis C. (2008). Modelling of cavitation in Diesel injector nozzle holes, *J. Fluid Mech.*, 616, 153-193 10.1017/S0022112008003777
5. Giannadakis E., Papoulias D., Gavaises M., Arcoumanis C., Soteriou C. & Tang W. (2007). Evaluation of the predictive capability of diesel nozzle cavitation models, SAE Technical Papers 2007-01-0245 http://delphi.com/pdf/techpapers/2007-01-0245.pdf
6. Gavaises M. (2008). Flow in VCO Nozzles with Cylindrical and Tapered Holes and Link to Cavitation Erosion and Engine Exhaust Emissions, *Int. J. Engine Research*, 9 (6), 435-447 10.1243/14680874JER01708
7. Stockner A.R., Ibrahim D.R., Gavaises M. & Theodorakakos A. (2011). *Methods of predicting cavitation damage*, US Patent 7,912,687

The *Journal of Fluid Mechanics* and *International Journal of Engine Research* are considered to be top journals in their field and selected papers undergo rigorous peer review prior to publication as do papers for *SAE Transactions/Journal of Engines*. SAE runs the largest annual automotive event with typically more than 10,000 participants and around 3,000 papers published each year.

4. Details of the impact

The transport sector is responsible for approximately 22% of the world's global energy consumption. This is expected to double over the next two decades.[8] Two thirds of the world's liquid fuel will be consumed by diesel engines. As all diesel fuel cavitates within the fuel injection equipment (FIE) before being burned, fuel injectors represent the key technology for meeting current and forthcoming emission regulations imposed on all types of internal combustion engines (ICE). This was recognised recently by AVL, a world-leading engineering group.[9]

The experimental findings and computational tools for cavitation developed at City have influenced the design of the FIE and combustion systems developed by Toyota (Japan), Delphi (UK) and Caterpillar (CAT) (USA), three of only five FIE manufacturers serving the entire automotive industry worldwide.[10, 11, 12] City's cavitation model is currently adopted by these companies as a design tool for developing new injectors. Delphi have commented as follows:

'*[City's work] has assisted us in assessing the predictive capability of CFD [computational fluid dynamics] codes simulating cavitation, applying new models into our designs, obtaining better understanding for complex flow phenomena such as valve motion, high pressurisation effects and cavitation erosion. The results obtained as part of these projects helped our research & development team to develop better understanding of the flow processes in Common Rail Injectors for car engines. Furthermore, the investigations on cavitation and erosion prediction will contribute to the design of more durable injectors for the truck engine market, a necessary pre-requisite for future market expansion. The results from the CFD tool developed by your team have been used by our engineers to help guide design for the development of new injectors. It helps our R&D team to understand a number of phenomena and gives ideas to further explore and enhance our own results.*' [11]

The development of engines is a complex process requiring integration and performance optimisation of various components developed through testing procedures over many years. Confidentiality is required by industry which complicates the isolation of City's contribution to the final engine performance output. However, to demonstrate our impact, the three examples provided below summarise the technical solutions to specific problems that were developed and the feedback from the companies with whom we have worked.

Example 1: Concept design of automotive Diesel engine injectors (Toyota Motor Corporation)

Toyota Motor Corporation (Japan) supported an experimental project on the visualisation of cavitation in optically accessible real-size nozzle designs. We investigated the physics of multiple fuel injections, a technique currently implemented as the standard approach for emission control. The findings are the first to demonstrate the inter-relationship between multiple injection shots and this discovery allows industry to control injection shots more accurately. Denso, a partner of the Toyota Group, is currently manufacturing such nozzles on the basis of City's research findings, as demonstrated in their recent research publication.[13] Compared to previous designs, such engines demonstrate an increase of approximately 15% in overall thermodynamic efficiency and a more than threefold reduction in soot and NOx emissions prior to the application of after-treatment devices, thereby delivering environmental benefits alongside economic benefits to the company.

The Director of the Advanced Technology Division, Toyota, comments on the work undertaken with City: "*Toyota's role is to develop combustion systems and to demonstrate and request the necessary specifications to the nozzle to realise our combustion concept. There was much contribution from the collaborative study to design the combustion system. […] There are many advantages in a low compression ratio; e.g., higher power density, better fuel consumption, low NOx keeping low level of smoke. […] The results obtained through our collaborative research were very helpful for the estimation of fuel spray behaviour including its stability caused by some of the cavitation phenomena. [...] Better understanding of the nozzle flow including cavitation phenomena made it possible to estimate the location and the quality of the mixture inside the cavity. ..it is hard to evaluate your contribution quantitatively. However, I can argue that the current Toyota combustion concept couldn't [have been] created without our collaboration. I hope my comments demonstrate the importance of your research to the success of Toyota's automotive engines.*" [10]

Example 2: Cavitation damage of the CR200 series injector in heavy-duty Caterpillar/ Perkins engines.

In 2005, Caterpillar/Perkins faced a severe cavitation erosion problem in one of their newly launched engines equipped with the CR200 series injector nozzle. While in serial production, customers observed severe problems of excess smoke and even engine failure resulting from in-nozzle erosion and subsequent damage. Experimental and simulation work performed at City across a series of projects in partnership with Caterpillar (the most recent being an EU Industry Academic Project running 2012 to 2016) provided a new modified design of the CR200 nozzle tip[3] that featured a grooved needle. This design proved to be durable and with no detrimental effect on the overall powertrain performance (power output and exhaust emissions). Caterpillar has recognised the importance of this design, as indicated in their comments below, and the nozzle is currently under production.

'*The CFD code developed by your team together with the experimental validation carried out at*

City helped our engineering team to develop better understanding of the flow processes and cavitation and erosion minimisation. As a result, we were able to enhance the design of CAT fuel systems products, primarily fuel injectors. These products meet and exceed our customer expectations by maximizing product values through superior durability and reliability. The simulation methodology for cavitation and cavitation erosion has been implemented in our internal CFD code and is currently used by our engineers to support the design of advanced heavy duty fuel injectors, which enable CAT engines to combine the benefits of ultra-high injection pressure and fully flexible injection for optimised combustion across the engine speed range and to meet the stringent emission regulations.' Caterpillar Large Power and Growth Markets Division[12]

Example 3: Power generation Diesel engine injector (Caterpillar Fuel Systems)
In 2006, Caterpillar installed a new Diesel engine in a small village in Alaska with about 400 inhabitants, living in an extremely cold climate. The 1MW Diesel engine was the only power source to cover the electricity needs of the local community. After a few days of operation excess cavitation damaged the engine. New injectors had to be installed every few days, resulting in excessive operational costs to Caterpillar and serious psychological impact to the local community, which faced repetitive engine failures and blackouts. Experiments and simulations performed at City have provided a long-term solution to this problem through a new injector design. The new engine has been in continuous use since this time, providing stability of power supply and consequent benefits to this resident community and to other users of the engines with these injectors installed.[12]

The impact of City's research in injector nozzle design on the automotive industry is significant and longstanding, helping to reduce pollution and improving engine efficiency while also bringing associated economic benefits to the industrial partners involved in the work. Cavitation research is now being applied to marine engineering through projects funded by Wärtsilä (a market leader in diesel and natural gas engines, propulsion systems and power plant solutions in the marine and energy markets) and BAE Systems.

5. Sources to corroborate the impact

8. The Outlook for Energy: A View to 2040, Exxon-Mobil, 2012 (available on request)
9. Daum S, Gill D, Theissl H, *IMechE Conference on Fuel Injection Systems for IC Engines, London* (2012)
10. *Toyota Motor Company*, Japan, Letter of support, 2013
11. *Delphi Diesel Systems*, UK, Letter of support, 2013
12. *Caterpillar Fuel Systems*, USA, Letter of support, 2013
13. T. Hayashi, M. Suzuki and M. Ikemoto 'Visualization of Internal Flow and Spray Formation with Real Size Diesel Nozzle', *ICLASS 2012, 12 International Conference on Liquid Atomization and Spray Systems*, Heidelberg, Germany, September 2-6, 2012
14. Gavaises, M., Papoulias, D., Andriotis, A., Giannadakis, E. and Theodorakakos, A., 'Link between cavitation development and erosion damage if Diesel fuel injector nozzles', *SAE Paper* 2007-01-0246, 2007