Institution: University of Leeds		
Unit of Assessment: 12		
Title of case study: Flow modelling research leads to innovative and profitable products and systems		
Period when the underpinning research was undertaken: 2009 – 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:**
V.V. Toropov	Professor	01/04/2006 – 31/12/2013
H.M. Thompson	Senior Research Fellow, Lecturer, Senior Lecturer, Professor	01/08/1998 – date
N. Kapur	Research Fellow, Lecturer, Senior Lecturer, Professor	01/07/1999 – date
J.L. Summers	Senior Lecturer	01/08/1998 – date
G. de Boer	Research Fellow	01/01/2015 – 31/05/2015
	Research and Teaching Fellow, Lecturer	01/09/2016 – date
C.A. Gilkeson	Research Fellow, Research and Teaching Fellow, Lecturer	01/04/2009 – date
Period when the claimed impact occurred: 2014 – 2020		
Is this case study continued from a case study submitted in 2014? No		

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

Flow modelling research has created impact through improved product designs, increased product development capabilities, and better-trained technical staff. These enabled: (i) Parker Hannifin to develop filtration systems [text removed for publication]; (ii) Sandvik Coromant to develop new cutting tools with step-change improvements in reliability and lifetimes; (iii) GSK to optimise the performance of manufacturing systems for semi-solid and colloidal products; (iv) the NHS to benefit from: improved ambulance designs with lower fuel consumption, and modified ventilators and air-driven Venturi valves to improve the treatment of COVID-19 patients; and, (v) Asynt to bring flow chemistry to a wider group of chemists.

2. Underpinning research (indicative maximum 500 words)

Since 2009, research in the School of Mechanical Engineering (**de Boer**, **Gilkeson, Kapur, Summers, Thompson, Toropov**) has created new computer-based flow modelling and optimisation methodologies for a range of flow systems and products in the commercial and public sectors.

In Diesel Filtration Systems

Kapur and **Thompson**'s research on gas-liquid flow systems with droplets created an accurate flow optimisation methodology for droplet flows in the jet pumps of filtration systems used in diesel engines [1]. The research challenge was to develop, and validate, an accurate flow model with a computationally-inexpensive geometry parameterisation that could predict when shock waves form in the jet pump. **Kapur** and **Thompson** developed an accurate computer-based flow modelling methodology whose predictions agreed well with experiment and used it to investigate how the shape and geometry of the pump affected local pressure changes and shock formation [1]. **Toropov**'s research on meta-model building using the concept of the Moving Least Squares Method (MLSM) [2] was very effective in representing the results of their flow simulations in a computer-based design optimisation tool. This has been widely exploited within the company Parker Hannifin to bring about process and product optimisation.

In Twist-Drills

During a Knowledge Transfer Partnership project (KTP009868), **Thompson** and **Summers** developed flow models of the coolant flow and heat transfer when coolant flows out of coolant channels, over the cutting edge, and then interacts with chips created by the twist-drill cutting action [3]. The flow models correlated very well with experimental wear scar maps and the measured tool lifetimes. Flow modelling results were encapsulated in MLSM meta-models that enabled cutting tool geometry to be optimised accurately and efficiently for specified performance and sustainability objectives.

In Pharmaceutical Manufacturing

During his RAEng/GSK Chair in Pharmaceutical Engineering (2014–2019), **Kapur** worked with **de Boer**, developing new flow modelling methods for understanding and optimising the performance of industrial rotor-stator mixers, mixer wear mechanisms and cleaning systems [4].

In the NHS

<u>Emergency Response Vehicles (ERVs):</u>

During a Knowledge Transfer Secondment, **Toropov** and **Thompson** combined MLSM-based optimisation techniques developed in [2] with high fidelity Computational Fluid Dynamics (CFD) to optimise the aerodynamic design of emergency response vehicles (ERVs). They worked with **de Boer** and **Gilkeson** using flow modelling and optimisation techniques [2], validated by wind tunnel experiments, to optimise the aerodynamic design of ERVs, leading to >12% improvements in ERV fuel economy [5].

<u>COVID-19:</u>

Kapur applied flow modelling and optimisation expertise initially developed in [1] to modify Continuous Positive Airway Pressure ventilators and develop an innovative air-driven Venturi valve to improve treatments for COVID-19 patients.

In Chemical Flow Reactors

Kapur developed flow modelling and optimisation techniques to create laboratory-scale, chemical flow reactors [6], which have brought the benefits of flow chemistry to a wider group of chemists.

Contributions from researchers outside the UoA

D. Copley and A. Mincher (Design Engineers, Parker Hannifin, 2009–present) provided experimental validation of the jet pump model. P.H. Gaskell and R.W. Hewson were former members of the Unit and contributed to the work reported in Ref. 5, but left the University of Leeds prior to this REF period. A.J. Blacker and B.N. Nguyen contributed to the work reported in Ref. 6, but are returned to UoA 8.

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

[1] Fan J, Eves J, Thompson HM, Toropov VV, Kapur N, Copley D, and Mincher A. Computational fluid dynamic analysis and design optimization of jet pumps. *Computers & Fluids* 46, 212–217 (2011). https://doi.org/10.1016/j.compfluid.2010.10.024

[2] Zadeh PM, Toropov VV, and Wood AS. Metamodel-based collaborative optimization framework. *Structural and Multidisciplinary Optimization* 38, 103–115 (2009). https://doi.org/10.1007/s00158-008-0286-8

[3] Johns A, Merson E, Royer R, Thompson H, and Summers J. A numerical investigation of through-tool coolant wetting behaviour in twist-drilling. *Journal of Fluid Flow, Heat and Mass Transfer* 5, 44–52 (2018). https://doi.org/10.11159/jffhmt.2018.005

[4] Rodgers A, de Boer G, Murray B, Scott G, and Kapur N. An investigation into batch cleaning using wash racks. *Food and Bioproducts Processing* 113, 118–128 (2019). https://doi.org/10.1016/j.fbp.2018.11.003

[5] Taherkhani AR, de Boer GN, Gaskell PH, Gilkeson CA, Hewson RW, Keech A, Thompson HM, and Toropov VV. Aerodynamic drag reduction of emergency response vehicles. *Advances in Automobile Engineering* 4(2), 1000122 (2015). https://doi.org/10.4172/2167-7670.1000122

[6] Chapman MR, Kwan MHT, King G, Jolley KE, Hussain M, Hussain S, Salama IE, Nino CG, Thompson LA, Bayana ME, Clayton AD, Nguyen BN, Turner NJ, Kapur N, and Blacker AJ. Simple and versatile laboratory scale CSTR for multiphasic continuous-flow chemistry and long residence times. *Organic Process Research & Development* 21(9), 1294–1301 (2017). http://dx.doi.org/10.1021/acs.oprd.7b00173

All of the above journals are internationally recognised with rigorous review processes and international editorial boards. The quality of the underpinning research being at least 2* is demonstrated by all six references.

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

Impact of Flow Modelling of Diesel Filtration Systems on Parker Hannifin (confirmed by Statement [A])

This UoA's flow modelling and optimisation research provided Parker Hannifin with a new product optimisation software design tool, which the company used successfully to design jet pump components of their droplet filters which were 20% more energy-efficient. The new Super Impactor crankcase ventilator—the engineering solution developed as a result of the Leeds modelling— reduces engine emissions in line with Euro 6 requirements, and boosts fuel efficiency.

The exploitation of the Leeds research by using the software design optimisation tool during the design of their Super Impactor product range has led to Parker Hannifin securing new business [text removed for publication]. The company is now employing [text removed for publication] additional people working in this product area. By January 2020, the annual sales revenue from the Super Impactor product range had grown [text removed for publication], with this figure rising steadily as the company continued to win new customers.

Impact of Coolant Flow Modelling on Sandvik Coromant (confirmed by Statement [B])

Coolant is used to improve drill life by transporting heat away from the cutting zone and evacuating waste material (chips) to prevent clogging. The coolant flow modelling and optimisation software tools developed by **Thompson** and **Summers** during Knowledge Transfer Partnership project KTP009868 have: (i) enabled the company to understand how twist-drill geometry affects overall cooling performance, reliability, and tool life; (ii) been instrumental in the development of the High-Performance Multi-Material Drills, which provide a step-change in reliability. Since their launch in March 2020, these have resulted in sales of [text removed for publication] up to September 2020. Despite the launch being seriously affected by COVID-19, the company estimate that their superior functionality will eventually result in annual sales of [text removed for publication].

The project led to an important culture change in the company through the provision of new knowledge, training and software tools to over 60 Sandvik technical staff in Sheffield, Coventry, Rovereto (Italy), and Sandviken (Sweden). The company now values flow modelling so highly that it has established a new R&D Modelling and Simulation team to provide flow modelling resources to the wider Sandvik Group and that this "*has been justified and formed based on the flow modelling research carried out on this KTP"* [B].

Impact of Flow Modelling of Pharmaceutical Manufacturing Systems on GSK (confirmed by Statement [C])

This UoA's flow modelling research in pharmaceutical manufacturing has "*enhanced significantly GSK's scientific understanding of semi-solid and colloidal systems*". It has been used by GSK to develop process understanding and to optimise the performance of the handling of white soft paraffin; rotor-stator mixers and mixer scraper blades; and, in the cleaning of systems used in production of creams and ointments. Furthermore, the training materials and courses that **Kapur** has delivered to over 150 GSK technical staff, in person and remotely, have led to "*substantial improvements in the technical capabilities of GSK staff"* in process engineering and flow modelling.

Impact of Flow Modelling on the NHS

<u>NHS Ambulance Services (confirmed by Statement [D]):</u>

Our research published in [5] convinced the Yorkshire Ambulance Service (YAS) to commission new, more aerodynamically-efficient ambulances. Since July 2013, YAS have operated 43 of these new vehicles, which have achieved an improvement in the average fuel efficiency from 16–18 miles per gallon to 26 miles per gallon, with savings of [text removed for publication] in fuel costs per annum. Our research [5] has been incorporated into the UK design specification for ambulance design, offering reductions in fuel consumption [text removed for publication], and ambulance manufacturer Cartwright has implemented the design for Yorkshire emergency response vehicles. It was also a recommended innovation in Lord Carter's review of Ambulance Services (Ref. [5] is cited on p 52): https://improvement.nhs.uk/documents/3271/Operational_productivity_and_performance_NHS_Ambulance_Trusts_final.pdf

<u>COVID-19 (confirmed by Statement [E]):</u>

Kapur worked with Leeds NHS Trust to apply his flow modelling expertise to optimise design modifications to Continuous Positive Airway Pressure (CPAP) machines and to develop an innovative air-driven Venturi valve to improve treatment of COVID-19 patients. The modified CPAP machines were used to treat >30 patients successfully in the first wave and were ready for use in the later COVID-19 waves. The valve places less burden on hospital infrastructure than other available designs, including efficient oxygen utilisation, and provides crucial additional treatment capacity should patient numbers outstrip existing CPAP and ventilator provision. These approaches and equipment have been adopted by other NHS Trusts.

Impact of Flow Modelling on Chemical Flow Reactors (confirmed by Statement [F])

Asynt Ltd created a commercial flow chemistry platform based on **Kapur's** prototypes [6], creating [text removed for publication] sales between January 2019 and October 2020. This is significant for an SME and enabled them to secure [text removed for publication] to bring further flow chemistry technologies to market, benefitting a wider group of chemists, and providing additional employment in the UK machining industries.

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

[A] Letter from the Division Engineering Manager, Parker Hannifin, 17 December 2020.

[B] Letter from the Product Group Manager, Sandvik Coromant Ltd, 19 November 2020.

[C] Letter from the NPI-PT Director, GSK, 8 July 2019.

[D] Letter from the Environmental & Sustainability Manager, Yorkshire Ambulance Service, October 2020.

[E] Letter from a Consultant in Anaesthesia and Intensive Care Medicine, St James' University Hospital, Leeds, 5 November 2020.

[F] Letter from the Managing Director, Asynt Ltd, 9 November 2020.