Institution:
University of Cambridge

Unit of Assessment:
UoA10

Title of case study:
Ink Jet Printing

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

Research carried out by Professors Hinch and Rallison at the University of Cambridge determined how ink jet printer fluids behave when emitted from the printer head. The research findings have been used by industry to optimise the design of the printer. Xaar, the world-leading independent supplier of industrial inkjet printheads which uses a drop-on-demand mode, has used the results of this research to improve the design and operation of its ink-jet printers to its own commercial benefit and to the benefit of the users of its printers.

2. Underpinning research (indicative maximum 500 words)

Professor E.J. Hinch (Lecturer 1975-1994, Reader 1994-1998, Professor 1998-date), and his research group including Professor J.M. Rallison (Lecturer 1985-1998, Reader 1998-2007, Professor 2007-date), at the University of Cambridge Department of Applied Mathematics and Theoretical Physics (DAMTP) have conducted fundamental research on the behaviour of visco-elastic fluids; the microstructural origin of their rheology (20 papers), the flow dynamics resulting from that rheology (20 papers), and how to compute such flows (6 papers). Hinch has also been interested in how jets break up into drops (3 papers).

Polymers are added to printing inks to inhibit undesirable splattering when a drop hits the paper. Adding too much polymer, however, can stop a jet breaking up into drops. The essential mechanism is that the polymers alter the surface tension forces that influence the way a continuous jet breaks into drops. The way that polymers affect the capillary forces squeezing a jet was investigated by Hinch in [Ref 3] in 1997.

In order to provide useful results accurate computational models are needed. Computing viscoelastic flows has a long history of failures. The problem lies in a proper mathematical treatment of the hyperbolic equation governing the evolution of the elastic part of the stress tensor. From 1995 to 1997 Hinch and Rallison developed an appropriate method to compute these flows in a simplified axisymmetric geometry [Refs 4 and 5] and later extended the axisymmetric code to a fully three-dimensional code to account for variations associated with nozzle geometries. That research led to the discovery by numerical simulations of a drop-on-demand printer of a very curious way in which drops are formed as a jet breaks up [Ref 1]. The predictions have been recently confirmed by experiments performed [Ref 2].

The viscoelastic codes developed by Rallison were for applications where inertia is negligible. The ink jet printing application, however, has significant inertia. The effects of inertia were added to Rallison's code by O.G. Harlen and N. Morrison, former students of Rallison and Hinch, working together at the University of Leeds. This work was independently verified by Hinch with J. Etienne (Research Associate at DAMTP from 2005 to 2007) who added viscoelastic effects to a pre-existing inertial code [Ref 6].

This research was supported through a major collaboration with the ink-jet printing industry, with 3 EPSRC grants involving 5 UK university departments and 8 UK companies. The aim of the collaboration was to understand scientific issues in ink-jet-printing and to improve the design, operation and performance of ink-jet printers.

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

1*. Day, Richard F., Hinch, E. John & Lister, John R. 1998 Self-similar capillary pinchoff of an inviscid fluid. Phys. Rev. Lett. **80**, 704-707, DOI: 10.1103/PhysRevLett.80.704. (98 cites)

2*. Castrejon-Pita, J.R., Castrejon-Pita, A.A., Hinch, E.J., Lister, J.R. and Hutchings, I.M. (2012) Self-similar Breakup of Nearly-inviscid Fluids. Phys. Rev. E. **86**, 015301, DOI: 10.1103/PhysRevE.86.015301.

3*. Entov, V.M. & Hinch, E.J. 1997 The effect of a spectrum of relaxation times on the capillary thinning of a filament of elastic liquid J. Non-Newtonian Fluid Mech. **72**, 31-54, DOI: 10.1016/S0377-0257(97)00022-0. (107 cites)

4. Harlen, O.G., Rallison, J.M. & Szabo, P. (1995) A split Lagrangain-Eulerian method for simulating transient viscoeasltic flows. J. Non-Newtonian Fluid Mech. **60,** 81-104, DOI: 10.1016/0377-0257(95)01381-5.

5. Szabo, P., Rallison, J.M. & Hinch, E.J. 1997 Start-up of flow of a FENE-fluid through a $:1:4 constriction in a tube. J. Non-Newtonian Fluid Mech. **72**, 73-86, DOI: 10.1016/S0377-0257(97)00023-2.

6. Etienne, J., Hinch, E.J. & Li, J. 2006 A Lagrangian-Eulerian approach for the numerical simulation of free-surface flow of a viscoelastic material. J. Non-Newtonian Fluid Mech. **136**, 157-166, DOI: 10.1016/j.jnnfm.2006.04.003.

*Research references which best reflect the quality of the underpinning research.

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

The major impact of this research has been its use by one of the companies in the EPSRC consortium. Xaar is the world-leading independent supplier of industrial inkjet printheads and uses a drop-on-demand mode. As a direct result of the research described above the company was provided with new understandings of the ways in which the inks they use behave when they are emitted from nozzles and impact on paper. It was also provided with new validated numerical codes that allow it to predict quantitatively the behaviour of the ink depending on its viscoelastic properties. Consequently, Xaar is able to make informed design decisions based on validated models of the ink behaviour, which have the capability to improve the design and performance of the printers.

Xaar has used the understanding of visco-elasticity to develop new combinations of printer heads and inks, and to identify rogue inks that underperform. While it is difficult to place a quantitative economic benefit to these developments, it is clear that the development of new printer heads and inks has both given the company a competitive advantage and provided a better performance to its customers. For example, Xaar provides an 'ink optimisation process' to design inks for specific applications based on Professor Hinch's research. Former Technical Director of Xaar and consultant during the impact period writes:

"these activities have been quite remarkably successful, and are founded on the understanding and development of rheological theory by Professor John Hinch who supervised Jocelyn Etienne, Oliver Harlen and Neil Morrison (the latter two now at Leeds University – part of the consortium) who have developed simulations of ink jetting for the consortium. As well as this, Professor Hinch has advised on all aspects of understanding of rheology and surface tension effects during the course of the two projects. Two instrumentation techniques have emerged from this as well as the successful simulation of jetting."

He further adds that

"The Ink Jet Research Centre [of which Professor Hinch is a member] at the Institute for Manufacturing was set up to address these problems and has formed a consortium of academic institutions and commercial partners. The commercial partners together represent more than £1B of annual business for the UK (much of it based in the Cambridge area)." [1]

Xaar's products sell worldwide and they currently have a turnover of 86M and invest between 8% - 10% in R&D. [2]

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

[1] Statement from former Technical Director of Xaar

[2] Xaar annual report 2012