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Steven Michael Roper

Research Areas

- In general, fluid and solid mechanics with solidification and other thermodynamic effects, especially connected with problems in materials science.
- **Theoretical Materials Science**
  Thermodynamics, phase change. Diffusion in binary alloys. Elastic effects. Microstructure evolution.
- **Growth of nanowires**
  Thermodynamics of nanostructures and their evolution through solidification, surface diffusion. Diffusion in binary alloys. Elastic effects.
- **Convection in Mushy layers**
  Solidification of multi-component alloys and subsequent dynamics of mushy layers. Flow in reactive porous media, chimney formation and interaction.
- **Fluid driven fracture**
  Flow of fluids in cracks, couples elasticity and fluid dynamics. Applications to geophysics and oil recovery.
- **Properties of non-linear integro-differential equations**
  Such equations arise in connection with fluid driven fracture, in flag-flapping and other problems with slender geometries.

Education

2005	• PhD Applied Mathematics, Department of Applied Mathematics and Theoretical Physics, University of Cambridge. Thesis title — “Theoretical Models for Dyke Trajectories and Geometries”. Additional courses taken in solidification, asymptotic methods and computational methods
2001	• Certificate of Advanced Study in Mathematics. Passed with distinction. Courses in very viscous flows, elastic waves, mixing and transport, fluid dynamics of swimming organisms, environmental fluid dynamics, magnetohydrodynamics, non-Newtonian fluid dynamics, computational fluid dynamics, atmosphere-ocean dynamics, laboratory demonstrations in fluid dynamics and general relativity. Essay on numerical methods for singular and hyper-singular integral equations.
2000	• BA (Hons) 1st Class, Pure and Applied Mathematics, University of Cambridge.
1997	• A-level: Mathematics (A), Further Mathematics (A), Chemistry (A), Physics (A), General Studies (A)
1995	• GCSE: Mathematics (A*), Science (double A*), Geography (A*), History (A), French(A), Design and Technology (A), English (A), English Literature (A)

Scientific Career

2007–present	• **University of Glasgow**. RCUK Fellow in Mathematics.

Scientific Career (continued)

2005–2007	• **Northwestern University**. Post-doctoral research associate. Research in solidification science, on the development of chimneys in mushy layers, involving numerical methods and asymptotic analysis. Growth of nanowires via vapour-liquid-solid mechanism through simple models of solidification and diffusion.
2001–2005	• **University of Cambridge**. Studied fluid driven fracture as a mechanism for the migration of magma in the Earth's crust and in laboratory analogues. Solved coupled elastic-fluid problems using asymptotic and numerical methods. Performed numerical analysis of common methods for the solution of crack openings. Thesis title "Theoretical Models for Dyke Trajectories and Geometries". Supervisor – Prof. John R. Lister.

Publications

- Roper, S. M. & Lister, J. R. 2005 Buoyancy driven crack propagation from an over-pressured source. *J*. Fluid. Mech. **5**36, 79–98.
- Roper, S. M. & Lister, J. R. 2007 Buoyancy-driven crack propagation: the limit of large fracture toughness *J*. Fluid. Mech. **5**80, 359–380.
- Roper, S. M., Davis, S. H. & Voorhees P. W. Forced convection in a mushy layer with sidewall heat-losses. *M*at. Met. Trans. A **3**5, 1069–1079.
- Hoyle, R. and Jefferson, D. and Leese, R. and Noble, S. D. and Roper, S. 2003. Network design for urban light transport. *E*uropean Study Group with Industry, 46th ESGI [Bristol 31/3/2003 - 4/4/2003]
- Roper, S. M., Davis, S. H., Voorhees P. W., Golovin, A. & Weiss, M. Steady growth of silicon nanowires via the VLS mechanism. *J*ournal of Applied Physics **102**
- Roper, S. M., Davis, S. H. & Voorhees P. W. The rigid-lid assumption in mushy-layer convection. (Accepted)
- Brush, L. and Roper, S. M. Evolution of a non-Newtonian foam. (Submitted)
- Roper, S. M., Davis, S. H. & Voorhees P. W. Localisation of mushy-layer convection by background flow. (In preparation)

Presentations

2007	• University of Washington, Applied Mathematics Seminar, "Mushy-layer convection"
2006	• APS DFD, Tampa, FL, "Localisation in mushy-layer convection by background flow"
2006	• University of Buffalo, Cornell. "Fluid driven fracture in geophysics"
2006	• UCSD, UCSB. "Mushy layer convection with sidewall heat losses"
2006	• University of Michigan "Mushy layer convection with sidewall heat losses"
2005	• APS DFD, Chicago, "Mushy layer convection in the presence on sidewall heat losses"
2005	• ESAM, Northwestern University, "Fluid-driven fracture: the limit of large fracture toughness"
2004	• BAMC, Norwich UK, "Fluid-driven fracture: the limit of large fracture toughness"
2003	• DAMTP, University of Cambridge "Fluid-driven fracture"
2003	• APS DFD, New Jersey, "Buoyancy driven crack propagation from an over-pressured source"

Workshop, study group and conference participation

2006	• APS, Division of Fluid Dynamics
2006	• Iowa State University, Ames, IA. Directions in Solidification. Participant
2005	• APS, Division of Fluid Dynamics.

Workshop, study group and conference participation (continued)

2003-2004	• Participation in the 43rd and 46th European Study Group in Industry. These week long study groups allow industrialists to present problems of practical importance to around 80–100 mathematicians and physicists. A week is spent exploring the problems and culminates in the presentation of the solutions to the industrialists. Special lectures are also given. I participated in a graph-theory/optimisation problem concerned with a transport system and in discussions concerning a problem in fibre glass production.
2003	• APS, Division of Fluid Dynamics
2001	• Participation in the NERC Geophysical Fluid dynamics summer school. Attended lectures on solidification, fundamental fluid dynamics, ocean physics and climate science. Conducted experiments in porous media flow and double diffusion.

Teaching Experience

2006,2007	• **Northwestern University**.Stand-in lecturer for undergraduate calculus and graduate-level course on Hyperbolic Systems and Waves. Prepared lecture material and delivered lectures.
2006	• **Northwestern University**. Responsible for the supervision of a Northwestern materials science undergraduate during his summer research project. Met each week to discuss progress and steer the direction of the research.
2001–2005	• **University of Cambridge**. Supervisor of undergraduate mathematicians, giving tuition to pairs of students in Mathematical Methods, Fluid Dynamics, Theoretical Geophysics, Differential Equations and Waves. Assessed and reported on students' progress.
2003–2004	• **NERC summer school in Geophysical Fluid Dynamics**. Computational and lab demonstrator for NERC geophysical fluid-dynamics summer school. Set-up demonstration equipment and explained a variety of fluids experiments.

Service

2005–2007	• Acted as a referee for the Journal of Fluid Mechanics
2005	• Demonstrated fluid dynamics experiments to the public as part of Mathematics Open Days

Skills

Computer	• (Proficient) Fortran, Gnuplot, LaTeX, MatLab, Maple, Postscript.
Computer	• (Working knowledge) C, C++, IDL, Perl, Awk, Bash, Mathematica, HTML, Microsoft.
Languages	• Basic french
Driving	• Full, clean driving licence
Other	• Participation in UK-GRAD school, a five day course designed to develop team-building skills, improve time-keeping and understand assertiveness.

Other Employment

2000	• **Summer student**. GCHQ, Cheltenham, United Kingdom. Gave presentations to senior management and conducted research.
1998-1999	• **Design assistant**. Lax & Shaw glass-works, Leeds, United Kingdom. Responsible for the modification of technical drawings of bottle-making equipment in response to customer requests and industry standards. Ensured the accurate and timely repair of equipment and delivery of necessary information to all parts of the factory.

Referees

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Teaching Statement

I have been fortunate, throughout my academic career, to have had the opportunity to teach in a variety of capacities. As a PhD student I taught undergraduate mathematicians in smalls groups, covering problem sets distributed by their lecturers. I have experience in assessing work, scheduling the tutorials and liaising with college staff to report the students' progress or difficulties. In this capacity I have taught fluid dynamics (inviscid and viscous), theoretical geophysics (elastic waves, internal waves, seismology and fluid dynamics in rotating systems), differential equations and mathematical methods. I would be happy to lecture or give tutorials in any of these areas in the future.

During my post-doctoral position I have supported the academic staff at Northwestern University by giving the occasional lecture on undergraduate calculus and a week of lectures at graduate level on hyperbolic systems and nonlinear waves. This involved lecturing at a moderate (50) number of students for an hour at a time and required me to prepare the lecture material and interact with the audience. With this lecturing experience I feel enthusiastic at the prospect of teaching at university level.

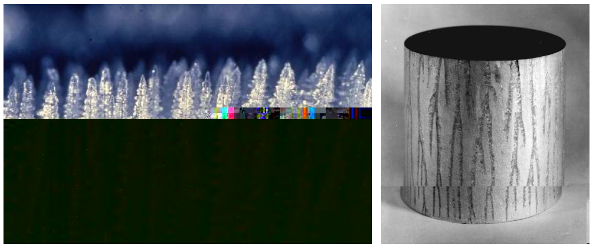
Also during my post-doctoral position I have been responsible for an undergraduate as he conducted a summer research project. This involved scheduling weekly meetings, directing the student's learning and research and providing the numerical and theoretical tools required for the student to complete the project and also equip the student with transferable skills for their future.

With the teaching experience described above I feel confident that I would enjoy and be successful at lecturing applied mathematics/physics courses. I would be capable of teaching fluid and solid mechanics, some thermodynamics, and mathematical methods, but would also be happy to teach courses I am not as familiar with as I still find that this is the best way to learn new material. I would be keen to develop a course in mathematical materials science, with a syllabus of solidification and phase change, fluid dynamics and solid mechanics, equilibrium thermodynamics, some quantum mechanics and numerical methods as appropriate. In general in any course I developed I would include some component of computation and application to industrial problems, as I believe this offers to the students a chance to develop useful skills, whatever their future career path.

Research Statement

My research interests lie broadly in the modelling and analysis of fluid and solid mechanical problems and of problems in materials science, particularly in the interactions between fluid and solid materials. This interaction could be mechanic, involving the flow fluid and deformations of confining solids, or thermodynamic, involving the phase transformations between liquids and solids and their implications for fluid flow. I would like to continue to develop my knowledge of, and research activity, within these fields and make connections with materials science, where an understanding of the coupling between elastic, fluid and thermodynamic effects is important.

Mushy layer convection



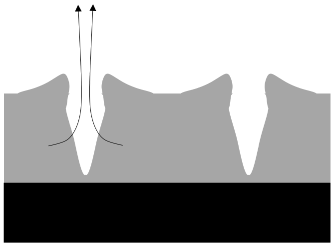
(left) Dendritic “Mushy Layer” composed of crystals of pure NH_4Cl and liquid water with dissolved ammonium chloride. From Hallworth, Huppert and Worster (1990). (right) A solidified ingot of an alloyed metal showing the defects that arise as a result of chimney formation. (From `http://www.icaen.uiowa.edu/b̃ecker/solcast.html`, in turn from photos of A.F. Giamei, UTRC)

The problems that arise in alloy solidification are relevant to both geophysics, materials science and industrial casting processes. When an alloy is solidified, one component of the alloy is usually preferentially solidified over another, leading to rejection of the remaining components ahead of the solidification front. The composition of the liquid ahead of the front affects the local melting temperature. It is possible that the concentration gradients and temperature gradients produced on solidification are such that the liquid is supercooled (at a lower temperature than its melting temperature) ahead of the front. This situation leads to a morphological instability of the interface and the growth of a complicated dendritic region, which separates the completely solid and completely liquid regions (see figure). This region is called a *mushy layer* and is often modelled macroscopically as a reactive porous medium (one that can change its solid fraction as a function of the local thermodynamic conditions). If gravity acts to produce an unstable density gradient in the mushy region a bifurcation to convection can occur, depending on the system parameters. Convection causes fluid motion, which alters the structure of the mushy layer and can create completely liquid chimneys connecting the solid region to the liquid region. These channels are responsible for a redistribution of solute in the system and play a role in sea-ice formation as well as being the source of defects in castings of multicomponent alloys.

There has been some published work on the structure of chimneys and their interactions and I would like to develop the analysis of the equations governing a mushy layer in the regime where chimneys form in order to understand their interactions. The solutions to the governing equations are controlled by a large set of non-dimensional parameters, the most important of these being the mush Rayleigh number

$$R_m = \frac{\Pi^* g \Delta\rho H}{\kappa\nu}$$

which measures destabilising buoyancy ($g\Delta\rho$) and ease of flow in the mush (permeability Π^*) of depth H, against dissipation in the mushy layer (ν) and diffusion of buoyancy (κ). Diffusion of buoyancy occurs as rising fluid equilibriates its temperature and concentration with its surroundings and the density contrast decreases. Other parameters characterise the effects of latent heat $\mathcal{S}$, concentration before solidification $\mathcal{C}$, viscosity in the liquid layer (Prandtl number σ) and a Darcy number $\mathcal{H}$. The largeness of the parameter set gives rise to a rich set of behaviours and the opportunity for asymptotic analysis to elucidate the rôle of each physical effect.



Schematic of mushy layer (grey), solid (black) and chimneys. Chimneys have been observed to interact, with some strengthening and others disappearing over time. The chimneys act as a source of buoyancy in the liquid, forming plumes.

I intend first to understand the structure of chimneys in limits appropriate both to salt systems (e.g. the mush seen in figure) and metallic systems, using existing theories as a basis to pursue an asymptotic and numerical investigation. I would like to derive simplified models of chimneys and their basins of attraction, extend the analysis to include two chimneys and finally produce a simple dynamical system, describing the location and strength of multiple chimneys in a mushy layer. The effect of flow in the liquid region would also be included, as the plume generated by a chimney provides an important coupling between the mushy layer and the liquid region.

Fluid driven fracture

In the Earth's crust there are pockets of fluid filled with magma, fed by the underlying mantle. Buoyancy forces or background stresses in the solid crust cause the fluid in the pockets to flow. If sufficient stress is concentrated in the solid, the rock may break and extend the region occupied by fluid, a process known as fluid-driven fracture. A manifestation of this can be seen in dykes, where the pocket of fluid takes the form of a long crack carrying magma vertically upwards. Solidification of the rock and subsequent erosion of the surrounding sedimentary rock reveals the structure. Sometimes the dykes make it to the Earth's surface where they are dramatically called "curtains of fire".

A "curtain of fire" in the Kilaiea region of Hawaii near the Pu'u 'O'o volcano (out of view at lower left). This is one of a series of eruptions during 1983–1986 which usually lasted less than a day and occurred approximately once a month. The width is a few metres and length of the order of kilometres. Photograph by G.E. Ulrich on July 18, 1986, by kind permission of the US Geological Survey.

The mathematical analysis of fluid fracture proceeds in several stages, the first is to relate the crack opening to the forces on the crack faces. The theory of linear elasticity is used, and the problem becomes that of finding complex functions which are analytic in the region cut by the cracks and with prescribed jumps on the crack faces. The stresses on the crack faces are used as boundary conditions for the flow of fluid in the crack, which is solved by exploiting the long thin geometry of a crack. The resulting set of partial differential equations relate the local rate of crack opening $\partial h/\partial t$ to the elastic pressure p_e, which is in turn related to to the crack opening via an integral transform. A fracture criterion is used to select the correct solution from a family of solutions to the equations. The solutions exhibit a rich behaviour.

In future I would like to develop models for fracture in gelatin, and for fluid-filled cracks with non-planar boundaries. This would involve an asymptotic analysis of the equations of elasticity and solution of the fluid problem inside the crack.

Growth of nanowires

During my post-doc I have been involved in the study of the growth of nanowires. Nanowires are rods of semi-conductor (such as silicon or germanium) which are 10–100 nm in diameter and can micrometres in length. They have desirable properties for the construction of nanoscale structures and in electronic applications. They can be grown via a technique known as Vapour-Liquid-Solid deposition, in which a catalyst particle (usually gold) is melted on a substrate, forming an alloy. The atmosphere surrounding the droplet contains the desired semi-conductor in a molecular compound (silicon, for example as silane SiH_4), the decomposition of which is enhanced by the catalyst droplet. The droplet absorbs the semi-conductor until a certain super-saturation is achieved and the nanowire column precipitates at the base of the droplet. A variety of morphologies exist depending the precise nature of the component elements and the growth conditions. Straight wires, branched wires and exotic helical wires have all been observed. My research in this area has been to examine the simplest case of straight nanowire growth, and to obtain a quantitative model that relates the growth rate and diameter of a silicon whisker to the sliane flux of the surrounding atmosphere. The next step is to determine the stability of the solution, where the emphasis is not only on learning the critical conditions and wavelength of any instability, but understanding the mechanism.