Institution: Aberystwyth University

Unit of Assessment: 10: Mathematical Sciences

Title of case study: Advances in Mathematical Modelling of Hydraulic Fracture Improve the Performance of Existing Simulation Tools.

Period when the underpinning research was undertaken: 2010- 2018

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 Gennady Mishuris	Professor	1 July 2007 - present
Dr Michal Wrobel	Visiting Research Fellow Marie Curie Research Fellow	10 June 2011- 31 March 2012 1 June 2012- 28 February 2017

Period when the claimed impact occurred: September 2013 to present

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

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

A rigorous numerical algorithm has been developed by Aberystwyth University (AU) researchers to improve the performance of software that deals with fluid-solid interactions, particularly the propagation of fluid-filled cracks. This was used by major companies in the petroleum industry to increase the speed and accuracy of their hydraulic fracture simulators, giving them a competitive edge and increasing their market share. Knowledge-exchange workshops with industry has led to better-informed scientists with the confidence to persuade policy-makers to implement hydraulic fracture at new sites across Europe and Russia.

2. Underpinning research (indicative maximum 500 words)

The Mathematical Modelling of Structures, Solids and Fluids Group at AU has expertise in Solid Mechanics, utilising numerous approaches including modelling, accurate mathematical analysis, numerical simulation and experiment. The group is led by Mishuris, an internationally renowned expert in Wiener-Hopf techniques, singular integral equations, mathematical modelling of fracture in continuous and discrete structures, micromechanics and fracture of composite materials, and fluid-solid interactions. The quality of his work has been recognised through numerous awards including an Alexander von Humboldt Fellowship, being appointed Belvedere Professor from the President of Poland, and a Royal Society Wolfson Research Merit Award (2016).

Hydraulic fracture occurs naturally, for example in subglacial drainage of water and in volcanoes. An understanding of the process is crucial in maintaining the safety of dams, geological waste repositories, and carbon capture and storage installations. In addition, hydraulic fracturing is one of the major techniques of reservoir stimulation (where it is called ‘fracking’) employed by the petroleum and gas industry.

In the process of hydraulic fracturing, fluid is pumped at sufficient pressure to create a crack. This in turn increases the flux of fluid into the material. Modern analytical, asymptotic, computational and experimental tools are used to study the coupling between fracture propagation and flow. However, two crucial factors are not commonly incorporated in fracture propagation models: (i) unsteady fracture propagation, which makes traditional fracture criteria in the form of equalities meaningless, and (ii) a lag between the fracture and the liquid front, which requires new formulations of coupled problems. Therefore, there was a need to improve simulations of the coupled problem of fracture propagation and fluid flow.

Mishuris and his team started to apply their research expertise to hydraulic fracture in 2010, securing the "HYDROFRAC" EU project [3.7]. Wrobel and Peck joined the team as PhD students, and subsequently secured postdoctoral positions in Aberystwyth to continue the research. The aim of the project was to enhance hydraulic fracturing techniques, thereby increasing the productivity of oil and gas reservoirs. This was an international collaboration involving Rzeszow University of Technology (Poland), New Mexico State University (USA) and industrial partners SINTEF (Norway) and EUROTECH (Poland).

The AU team was responsible for the formulation and modelling of the 3-D coupled problem of fracture propagation accompanied by complex fluid flow. They devised a procedure for the simulation of liquid flow in a propagating fracture and simulated the transport phenomena in a non-Newtonian fluid within a propagating crack. They validated these new codes and applied them to different regimes of hydraulic fracturing.

This new, efficient, hydraulic fracture algorithm uses a non-standard set of dependent variables and implements exact integration at all singular points of the domain [3.1; 3.2]. In contrast to the commonly used implicit level set method to trace the position of the crack front, the new model uses an explicit approach [3.3] that relies on calculating the magnitude of the fluid velocity at the crack front directly from these non-standard dependent variables. This idea initially surprised the research community working in this area but was later accepted as a valuable approach.

All propagation regimes (viscosity, toughness and leak-off dominated regimes), basic classic geo-mechanical models (PKN, KGD, Radial) and the commonly-used fluid rheologies were analysed [3.4; 3.5; 3.6]. The research group showed that the amended algorithm outperformed existing algorithms and were able to evaluate improved rigorous semi-analytical benchmarks [3.4; 3.5; 3.6].

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

3.1 **Mishuris, G**., **Wróbel, M**. & Linkov, A., *On modeling hydraulic fracture in proper variables: Stiffness, accuracy, sensitivity*. (2012). International Journal of Engineering Science. 61, 10-23. DOI: 10.1016/j.ijengsci.2012.06.005

3.2 **Wrobel, M**., & **Mishuris, G.** *Efficient pseudo-spectral solvers for the PKN model of hydrofracturing*. (2013) International Journal of Fracture, 184, 151-170. DOI: 10.1007/s10704-013-9847-y

3.3 Kusmierczyk, P., **Mishuris, G**., **Wrobel, M**. *Remarks on application of different variables for the PKN model of hydrofracturing: various fluid-flow regimes*. (2013). International Journal of Fracture, 184, 185-213, DOI: 10.1007/s10704-013-9867-7

3.4 **Wrobel, M**. & **Mishuris, G**. *Hydraulic fracture revisited: Particle velocity based simulation.* (2015) International Journal of Engineering Science. 94, 23-58. DOI: 10.1016/j.ijengsci.2015.04.003

3.5 Perkowska, M., **Wrobel, M**. & **Mishuris, G**. *Universal hydrofracturing algorithm for shear-thinning fluids: Particle velocity based simulation.* (2016). Computers and Geotechnics. 71, 310-337. DOI: 10.1016/j.compgeo.2015.10.005

3.6 Peck, D., **Wrobel, M**., Perkowska, M. & **Mishuris, G**. *Fluid velocity based simulation of hydraulic fracture - a penny shaped model*. (2018). Meccanica. 53(15),
Part I: the numerical algorithm, 3637-3650, DOI: 10.1007/s11012-018-0899-y
Part II: new, accurate semi-analytical benchmarks for an impermeable solid, 3637–3650. DOI: 10.1007/s11012-018-0903-6

Research Grants

3.7 Gennady Mishuris; HYDROFRAC: "Enhancing hydraulic fracturing on the basis of numerical simulation of coupled geomechanical, hydrodynamic and microseismic processes"; EC, FP7-PEOPLE-2009-IAPP Marie Curie, PIAP-GA-2009-251475; 2010-2014; EUR1,530,000 (GBP1,297,790 (11-2010), (with GBP GBP704,286 (EUR830,078 (11-2010)) for AU) https://cordis.europa.eu/project/rcn/95153/factsheet/en

3.8 Gennady Mishuris; British Council, "Internationalising Higher Education Programme – Ukraine" UA/022014/IHE01; 2014-2015; GBP5,000 https://www.britishcouncil.org.ua/en/british-council-announces-awards-exploratory-grants

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

The development of a more efficient algorithm for modelling fluid-solid interaction in hydraulic fracture has resulted in a variety impacts in the UK, Norway, Ukraine, Poland and Russia. Mishuris' recognised expertise has also enabled him to inform policy in this area.

Impact on Commerce

SINTEF is the largest independent research and development contractor in Scandinavia and one of the largest in Europe. Based in Norway, it contributes to value creation and increased competitiveness within the public and private sectors. Mishuris has collaborated with SINTEF for more than a decade and was part of a group of international experts invited to join the SINTEF project "Controlled Fracturing for Increased Recovery". This project aimed to further develop SINTEF's MATLAB Reservoir Simulation Toolbox (MRST) [5.1]. A special tip element proposed by Mishuris' team was implemented into the MRST software (MDEM module). SINTEF's Research Manager notes that this *'enabled us to improve the accuracy and speed of a hydraulic fracturing simulator developed at SINTEF. The improvement gives us a competitive edge and makes it easier to develop further projects on the basis of this software'* [5.2].

Other companies are also working on implementing the results of the HYDROFRAC project, including the software company Rockfield, who recognise the *'high demand in Carbon Capture, Oil & Gas R&D and industries to efficiently predict fracture propagation in all regimes.'* [5.3]

In 2017, the Russian oil company GAZPROM NEFT co-funded (with the Russian government) the CyberFRAC project, bringing together four Russian universities to create a new Hydraulic Fracture simulator. Mishuris was invited to advise this group, which subsequently adopted the results of the AU research to speed-up the calculations of the motion of the crack tip in the resulting simulator. This research is now central to the successful use of the software by GAZPROM NEFT, with the Deputy CEO for expertise and operational development reporting:

> *'High performance of the <<CyberFRAC>> simulator has already been confirmed: it is much faster and simultaneously more accurate than other comparable commercial software. This increases the efficiency of our technological operations and dramatically decreases the time to find the best available solution and to achieve the main goal: to improve productivity preserving high level of safety, especially since Gazprom Neft has significant oil fields in the Russian Western-Siberian and Arctic regions.'* [5.4]

Impact on Policy in Ukraine

As a result of the expertise in hydraulic fracture developed during the HYDROFRAC project, Mishuris has been influential in providing policy-makers with rigorous modelling of the fracking process to underpin their decisions.

In 2014, he secured British Council funding [3.8] for an exchange with Ukrainian partners to explore the exploitation of unconventional energy resources in the Ukraine. The preliminary results of this work were presented at the event 'Energy Policy and Politics (Ukraine-Russia)' in London in 2014 [5.5.1; 5.5.2, 5.5.3]. This led to the partners developing a relationship with

PETROPLY Research and Consulting Ltd, a Ukraine-based team of researchers and petroleum consultants, who were able to supply real data with which to test the AU algorithms.

Mishuris was then invited to join an international team of advisors, coordinated by PETROPLY and supported by Shell Exploration and Production Ukraine and Ukrainian Unconventional Gas Institute, tasked with improving forecasts of oil and gas development in Eastern Ukraine. They used the software developed at AU to assess the validity of their current operations, estimating water resource requirements, and developing practical recommendations for usage and optimisation of water and its reuse in technological processes [5.6].

Subsequently, and as a result of this increased confidence in the process of hydraulic fracture, and the ability of Ukrainian teams to perform it, the Ukrainian national oil corporation commenced extensive hydraulic fracture operations between 2016 and 2018. These were 'successful', and *'overall production and monetary effect exceeded all previous expectations'* [5.7]. The Director of AGS Construction, a service company operating in the Ukrainian oil and gas (O&G) industry, reports that this work has *'had significant impact on the configuration of the government long-term plan for the oil and gas industry.'* [5.8]

Impact on learning

This research on hydraulic fracture has enabled the development of a new generation of young researchers who are capable of accurately solving difficult multi-physics problems with an awareness of their applications.

The CEO of the Polish SME EUROTECH notes that the HYDOFRAC project has led to further development opportunities for funding and growth, and for 'the improvement of staff expertise'. In particular, a seconded researcher (Wrobel) was able to use mathematical insights from the project to improve the safety of UAVs, resulting in the company being able to *'provide more safety flights and build reputation on [the] market'* [5.9].

The availability of a faster simulator and a skilled workforce has had tangible benefits for the sector. The Ukrainian company AGS Construction have been able to *'analyse case studies more accurately'* with the *'very fast PKN simulator developed in Aberystwyth'* [5.8]. This has improved their reputation, saved money, and supported the growth in their workforce [5.8]. The CEO of EUROTECH also reports that his workforce has doubled since 2014 as a result of being able to employ trained staff [5.9].

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

5.1 See https://www.sintef.no/projectweb/mrst/ This software is available under the terms of the GNU General Public License, although the MDEM module is currently not freely available for commercial reasons.

5.2 Testimonial from SINTEF (Norway)

5.3 Testimonial from the CEO/Managing Director of ROCKFIELD (UK).

5.4 Testimonial from the Deputy CEO of Gazpromneft Science and Technology Centre (Russia).

5.5.1 Presentation given at workshop on policy making on energy Russia-Ukraine-UK "Russia-Ukraine-EU energy partnership towards Energy Security", London, UK. (11 September 2014) DOI:10.13140/RG.2.1.1199.4481

5.5.2 Blog regarding workshop on policy making on energy Russia-Ukraine-UK"Russia-Ukraine-EU energy partnership towards Energy Security" https://blogs.ucl.ac.uk/sustainable-resources/2014/09/18/towards-energy-security-the-russia-ukraine-eu-debate/

5.5.3 Programme for workshop on policy making on energy Russia-Ukraine-UK"Russia-Ukraine-EU energy partnership towards Energy Security".

5.6 Report on prospects for Ukrainian oil and gas production (Use of Water Resources in Prospective Development of Oil & Gas Industry of Ukraine)[Lang.: Ukrainian] https://www.researchgate.net/publication/303436590_Use_of_Water_Resources_in_Prospective_Development_of_Oil_Gas_Industry_of_Ukraine_Vikoristanna_vodnih_resursiv_v_kontekсti_rozvitku_naftogazovoi_promislovosti_Ukraini

5.7 Testimonial from the Director of Petroply Research and Consulting Ltd (Ukraine)

5.8 Testimonial from the Director of AGS Construction (Ukraine).

5.9 Testimonial from the CEO/President of EUROTECH (Poland).