Institution: Imperial College London

Unit of Assessment: 12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study: 13. Increased safety and efficiency of oil and gas process designs from improved flow assurance

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

Multiphase flow research at Imperial has developed bespoke software code, and provided unique data for validation of commercial codes used for oil-and-gas design. This research has enabled global oil companies (e.g. Chevron) to undertake successfully the design of deep-water production systems requiring multi-billion pound capital investments. This research has also allowed SPT Group (now owned by Schlumberger), one of the largest software (OLGA) providers to the oil industry, to maintain their position as market leaders.

2. Underpinning research (indicative maximum 500 words)

A major issue in multiphase flows is the ability to predict sudden flow regime transitions following a change of parameters (e.g. phase superficial velocities). These systems, however, have deformable interfaces interacting with turbulent fields that possess highly complex topology, and encompass a very wide range of length and time-scales. Making reliable predictions of multiphase flow regimes and their transitions is, therefore, a major research challenge, which has been addressed by researchers at Imperial since 1996 under the framework of the Transient Multiphase Flow (TMF) programme. This is a joint university-industry programme with 3 universities, Imperial College London (lead), Cranfield University and Nottingham University (and formerly Bristol) and 14 major oil-and gas and specialist 'design-house' companies: BP, Chevron, Petrobras, Statoil, Total, FMC, Grahnerne, Intecsea, Multiphase Solutions Kenny Ltd, ASCOMP, CD-Adapco, FEESA, SINTEF, Kongserbg Oil & Gas Technologies, SPT Group (part of Schlumberger).

The TMF programme was founded by Professor Geoff Hewitt in 1996 and sought to address the research challenges in multiphase flow directly through a two-pronged approach: the creation of unique experimental facilities that enable data measurements to be performed under realistic, industrial conditions; and the development of computer codes to predict flow regime transitions, and individual flow regime properties. The Imperial College researchers involved in TMF are:

- Professor Geoff Hewitt, FRS, FREng (experiments, 1996-present, Dept. of Chem. Eng. – Founder)
- Dr Raad Issa (one-dimensional, multi-fluid modelling, 1996-present, Dept. of Mech. Eng.)
- Professor Chris Lawrence (mathematical modelling, 1996-2006, Dept. of Chem. Eng.)
- Professor Omar Matar (mathematical modelling, numerical simulations, 2005-present, Dept. of Chem. Eng. – Director)
- Professor Stephen Richardson, FREng (thermodynamics, numerical modelling, safety, 1996-present, Dept. of Chem. Eng.)
- Dr Graham Saville (thermodynamics, high-pressure and high-temperature experiments, 1996-2008, Dept. of Chem. Eng.)

Specific research insights from work that was carried out at Imperial College under the TMF programme are outlined here.

The Imperial College TMF experimental rigs are of a scale and industrial relevance exemplified by the high-pressure ‘Water, air, sand, and petroleum (WASP)’ facility which is housed in the Chemical Engineering Department of Imperial College. It consists of a reclinable 37m-long test-section with a 78mm internal diameter. WASP is equipped with X-ray tomography sensors, Gamma-ray densitometry, and high-speed visualisation capabilities, which can yield hold-up information, and axial- and side-views of the complex interfacial structures accompanying the various multiphase flow regimes as a function of pressure drop or flow rates, temperature, and inlet conditions. In 2001 Prof Hewitt published work where laser-induced fluorescence and photo-chromic dye-tracing have been developed and deployed within the rig to examine, in detail, the flow properties of liquid-liquid and three-phase flows. [1]

Further experimental research led by Hewitt in 2006 [2] elucidated the initiation mechanisms of 'slug' flows, and showed that initiation is delayed at high pressures. Hewitt and Matar, and co-workers [3] showed that, in large-diameter pipes, slug-flow is by-passed completely. A two-beam X-ray system was also developed by Hewitt in 2005 [4], which allows tomographic images of multiphase (oil–water–gas) flow to be recorded, for accurate visualisations in pipe flows. Along with support from the industrial partner this work was supported from EPSRC grant GR/S17765/01

This experimental work was complemented by the development of a model (Transients In One-dimensional Multi-PHase flow -TRIOMPH) by Dr Raad Issa in 2003 [5], which demonstrated the ability of a two-fluid model to automatically capture the initiation of slugs, to follow their development as they travel along a pipe, and to calculate characteristics such as slug length and frequency [5]. Further models, such as the General Runge-Kutta Annular Modelling Program (GRAMP), were developed by Hewitt [6] to provide predictions of local void fraction, pressure gradient, entrained liquid fraction, and film thickness in annular flow.

The combination of Imperial's experimental work and the models developed, particularly those by Dr Issa, allowed reliable predictions of multiphase flow regimes and their transitions, and resulted in substantial benefits to the oil and gas industry as described in section 4 below.

3. References to the research (indicative maximum of six references)
* References that best indicate quality of underpinning research.

[1] S. Badie, C.P. Hale, C.J. Lawrence, G.F. Hewitt, "Pressure gradient and holdup in horizontal two-phase gas-liquid flows with low liquid loading", Int. Journal of Multiphase Flow, Vol 26, pp.1525-1543, (2000) DOI: 10.1016/S0301-9322(99)00102-0

*[2] P.M. Ujang, C.J. Lawrence, C.P. Hale, G.F. Hewitt, "Slug initiation and evolution in two-phase horizontal flow", Int. Journal of Multiphase Flow, Vol 32, Issue 5, pp. 527-552, (2006), DOI: 10.1016/j.ijmultiphaseflow.2005.11.005

[3] D. Peng, M. Ahmad, C. P. Hale, O.K. Matar, G.F. Hewitt, "Flow regime transitions in large diameter pipes", 7th Int. Conf. on Multiphase Flow, Tampa, FL, USA, May 30-June 4, (2010) http://ufdc.ufl.edu/UF00102023/00172

*[4] B. Hu, C. Stewart, C.P. Hale, C.J. Lawrence, A.R.W. Hall, H. Zwiens, G.F. Hewitt, "Development of an X-ray computed tomography (CT) system with sparse sources: application to three-phase pipe flow visualization", Exp. Fluids, Vol 39, Issue 4, pp. 667-678, (2005) DOI: 10.1007/s00348-005-1008-2

*[5] M.H.W. Kempf, R.I. Issa, "Simulation of slug flow in horizontal and nearly horizontal pipes with the two-fluid model", Int. Journal of Multiphase Flow, Vol 29, pp. 69-95, (2003) DOI: 10.1016/S0301-9322(02)00127-1

[6] M. Ahmad, D.K. Chandraker, G. F. Hewitt, P.K. Vijayan, and S.P. Walker, "Phenomenological modeling of critical heat flux: The GRAMP code and its validation", Nuclear Engineering & Design, Vol 254, pp. 280-290, (2013) DOI: 10.1016/j.nucengdes.2012.09.004

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

Oil-and-gas companies need to transport significant volumes of multiphase fluid long distances through pipelines from deep-sea beds. This is a process complicated by the complexity of multiphase flows. For instance, the intermittency arising from slug flow enhances pipeline erosion and increases the stresses on pipeline bends. Severe fluctuations in flow volumes also cause unwanted flaring at separators on oil platforms resulting in safety concerns and subsequent reduction in the operation capacity of oil plants. These issues give rise to design challenges and usually lead to design compromises that sacrifice efficiency and/or size of the processing plant. The oil-and-gas industry is therefore in need of validated predictive tools for flow assurance predictions.

Software company members of the TMF programme have been key in spreading the impact of the research. The slug capturing model in the TRIOMPH code developed at Imperial [5] has been embedded in two new commercial codes, namely LEDAFLOW issued by Kongsberg Oil and Gas Technologies and PROMPT being issued by Multiphase Simulation Ltd. One of the companies supplying consultancy and software to the oil-and-gas industry is FEESA Ltd, which is based in Farnborough Hants. The Managing Director of FEESA Ltd, states:

> "Though FEESA is a software company, it does not develop its own multiphase models, rather it gives engineers access to the multiphase models of others, such as the published (e.g. Beggs and Brill) and commercial models (i.e. OLGA-S and LedaPoint from SPT and Kongsberg, respectively). Though most developments in these tools are commercial in confidence to their developers, FEESA is aware that they do borrow ideas developed in TMF quite a lot. An example of this is the slug capturing model in LedaPoint which …. proved to be a more physically reasonable method for modelling slugs than the traditional slug tracking method. I'm sure Kongsberg would not have gone down this route without Raad [Issa]'s group in TMF blazing the way some years before. Better slug models mean more confidence in surge volume predictions, which lead to smaller design margins on topsides equipment, which can lead to designs being cheaper and more optimal. There is also a safety implication of reducing separator volumes on production facilities. In short, pressure is energy per unit volume and the less stored up energy there is on manned facilities the safer everyone is." [C]

Importantly, the codes are not credible without validation. The unique experimental information in relation to slug flow provided by Imperial research [1-4] has allowed successful validation, which in turn has led to the results of their predictions being accepted by the industry as accurate. This has enabled the oil-and-gas companies to determine the operating envelopes, flow regimes and associated design considerations as well as the energy requirements likely to be encountered in particular applications.

Two examples illustrating the contribution of TMF to the oil and gas industry are provided:

- SPT Group, now part of Schlumberger, is one of the largest software providers to the oil-and gas industry with an operating income of $29.6M in 2012. SPT has been actively associated with TMF since its foundation. The SPT group developed the single platform (OLGA), which is now the world leading product for multi-phase oil and gas flow prediction. Chief Scientist of SPT Group, states: *"These flows are complex and multiscale. Predicting their behaviour is central to this industry and continues to be of paramount importance to the UK economy: North Sea revenue alone is expected to raise >£11bn in revenues in 2011-12. TMF have championed the cause of making progress through reliance on sound and rigorous fundamentals. …In terms of the impact generated by TMF,* ***it is clear that the TMF-related research activities, both modelling and experimental, have led to significant improvements in our ability to simulate the essential physics of multiphase pipe flow, and thus to maintain our position as market leaders****… also through the training of high-quality researchers that have taken up important positions in the oil-and-gas industry, in oil-and-gas research and in SPT Group."* [B]

- Sr. Staff Scientist within Flow Assurance of Chevron (2nd largest western oil producing company) states: *"much of the equipment (separators, filters, multiphase flow lines, etc.) being installed would have not been possible without the knowledge obtained through TMF. Without the knowledge from TMF, some of the oil industry projects would have been too risky to proceed. Thus, it is possible to say that the impact of TMF on the oil industry is worth hundreds of millions of dollars."* [A]

The TMF collaborative programme allows immediate use of the research by the industrial partners. Additional routes through which the impact has taken place include the recruitment of TMF PhD students by TMF sponsors, and the consultancy work carried out by TMF academics on problems that are of specific interest to the sponsors.

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

[A] Senior Staff Scientist, Flow Assurance, Chevron to confirm the impact on equipment design

[B] Chief Scientist, SPT Group Norway to confirm the impact on the company and its ability to remain as market leader

[C] Managing Director, FEESA Limited to confirm the impact of the slug models on designs