Institution: University of Birmingham

Unit of Assessment: Mathematical Sciences

Title of case study: Mathematical Foundations of Flow Assurance Issues in the Petroleum Industry

1. Summary of the impact

This case study relates to research supported under contract by Statoil AS, one of the world's largest oil and gas companies, and is focused on two major issues of significance to that industry, namely, the mathematical modelling and analysis of (a) hydraulic two-layer gas/liquid flow in pipe lines and (b) wax formation in the interior walls of pipe lines transporting heated oil. These projects arose out of contacts between senior research staff at the Statoil Research Centre and the Nonlinear Waves group in the School of Mathematics. The theoretical research undertaken was designed to complement the major experimental programmes developed at the Statoil Research Centre and was performed in collaboration with scientists there. The work has provided Statoil with a reliable theoretical framework to contextualise and enable comparison with experimental results and to inform the design of future experimental programmes. In the larger context, the research has played a key role in advancing the capability of Statoil to design and implement more economical, energy efficient, and environmentally safe strategies for gas/oil delivery via extended pipeline networks. Statoil have stated that the benefit of access to robust flow models in the North Sea context is rapidly approaching an economic value of many billions of Norwegian kroner.

2. Underpinning research

In relation to the nonlinear waves project, previous theoretical models of two-layer gas/liquid flow in circular pipes, driven by prescribed upstream inlet flow rates, have been based around treating both the gas and liquid as inviscid fluids. In relation to the inviscid model, the uniform flow of the two-layers can undergo linear instability at critical prescribed flow rates. This instability is not a long-wave instability, and is related to the classical hydrodynamic Kelvin-Helmholtz instability at a shear layer interface. It was originally thought that this model, with the associated Kelvin-Helmholtz instability, may account for the transition, in two-layer gas/liquid pipe flow, from uniform flow to slug flow. However, detailed comparison with experimental work has revealed a number of serious flaws in this conclusion. In particular observations suggested that dissipation/friction are associated with the transition, and that the development of a hydraulic model would be essential in a rational and predictive theory for the transition phenomena. This research programme, from 2005-2010, led by D J Needham (Professor of Applied Mathematics) was undertaken with Statoil AS and began with the development of a two-layer hydraulic theory. Simplified evolution equations were developed for the situation when the underlying liquid layer is shallow compared to the overlying gas layer, the situation of practical interest identified by Statoil for gas/condensate pipe lines. The temporal stability of the uniform flow is examined via linearization of the evolution equations, and this leads to an equation of wave-hierarchy type with dissipation. The temporal stability of the uniform flow is shown to depend upon the Froude number of the liquid layer, which is related to the upstream volumetric flow rates in both layers. This criterion for hydraulic in stability leads to a long-wave maximum growth rate close to transition, and, moreover, the transition criterion is in qualitative, and some quantitative, agreement with experimental results. The roll wave structures have been identified as appearing through Hopf bifurcations, with a nonlinear selection mechanism associated with convective instabilities in the long wave profile 'tail'.

In relation to the wax deposition problem the programme of work, led by D J Needham, was undertaken with Statoil AS, from 2010-2012. We have proposed an entirely different approach towards modelling the deposition of paraffinic wax on the inside of the pipe wall, which has previously been based on isothermal material diffusion mechanisms, and has been largely unsuccessful. Our principal observation is that the crystallisation of wax is an exothermic process, meaning that wax will only be formed there when heat, as a result of the crystallization process, can be removed. Indeed, this explains why wax forms on the inside of the pipe wall, only when the exterior pipe wall is subject to sufficient cooling (we observe in passing that the diffusion model does not offer such a simple explanation for the deposition of wax on the pipe wall). The growth of the wax layer will thus be governed by the balance of heat supplied by means of convection to the wax layer from the oil phase and heat removed from the wax layer by means of conduction through the pipe wall. The problem that is obtained is a moving boundary problem of a generalised Stefan type, which has been analysed in detail via both analytical and numerical approaches, leading to a reliable and predictive tool for Statoil.

The work associated with the two-layer gas/liquid pipe line flow was performed under contract with Statoil AS by D J Needham, the late Professor A C King (University of Birmingham) and J Billingham (University of Nottingham) from 2005 to 2010. The work associated with wax deposition on the interior walls of heated oil pipe line flows was performed under contract with Statoil AS by D J Needham and B T Johansson (Senior Lecturer, University of Birmingham, until September 2012) from 2010 to 2012. The research has led to contract reports for Statoil, together with two substantial publications in high quality Applied Mathematics journals.

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

‘The development of slugging in two-layer hydraulic flows’, IMA JL Appl Math, 2008, 73, 1, 274-322 (D J Needham, J Billingham, R M S M Schulkes*, A C King) doi: 10.1093/imamat/hxm050

‘The development of a wax layer on the interior wall of a circular pipe transporting heated oil’ University of Birmingham, School of Mathematics Preprint Series 2012/04 (to appear in Q Jl Mech Appl Math) (D J Needham, L Amundsen*, B T Johansson, T Reeve)

* Author employed at Statoil Research Centre, Porsgrunn, Norway.

4. Details of the impact

The projects upon which this case study is based arose out of contacts between the Birmingham researchers and senior research staff at the Statoil Research Centre, Porsgrunn and were reported to Statoil beginning in 2008, leading to subsequent benefits for the company. Statoil AS is a fully integrated international petrochemical company (the Norwegian government being a 67% shareholder) with significant operations in 36 countries worldwide. By revenue, Statoil was ranked as the world’s 13th largest oil and gas company in 2010.

Flow Assurance is an accepted terminology in the oil industry; it defines the technology area that seeks to ensure uninterrupted flow from the oil/gas reservoir to the control platform.
Since the production from an oil/gas reservoir almost always includes gas, oil and water, ensuring uninterrupted flow requires having control of multiphase transport (oil+water+gas) in potentially very long pipelines (140km is the current limit. However, Statoil are working on a pipeline that is 600km long). Control of multiphase transport means: understanding pressure drop, understanding the presence of flow instabilities and being able to predict the amount of liquid/gas that a processing unit (platform) may receive an any one time (in order to be able to dimension the separators etc properly).

A theoretical approach to nonlinear waves in such pipe flows forms a fundamental part of the long-term aim to understand details of the flow structure better so that models can be significantly improved. These improved models can then be used to give better predictions of the flow behaviour so that the whole field (pipelines + processing units) can be dimensioned with more precision. Success with this achieves the following: 1) preventing over-dimensioning of systems (which is very expensive and may render a project uneconomical), 2) preventing unexpected bottle necks (it is very expensive to make modifications on an existing platform since production has to cease). Improving flow models is very much a brick-by-brick building process – since flow simulators contain many different sub models (eg for slug flow, stratified flow, dispersed flow etc) and all these models interact in a highly nonlinear way, it is not always evident how an improvement in one sub model may increase the overall predictive quality of the flow simulator.

The work reported in this case study on nonlinear waves is one of those bricks – it enables fundamental understanding which supports the long-term aim of developing better and more robust flow models. The impact of having access to such models is enormous. As reported by [redacted] (Leader, Multiphase Flow Research and Development Statoil AS) *‘In the North Sea context this is rapidly approaching an economic value of many billions of NOK’s’*.

Multiphase flow is one main branch of the Flow Assurance tree. The other main branch is related to control of pipe line deposits. Deposits come in many different forms, for example, sand, wax, hydrates, scale and asphaltenes. Some deposits (like sand) are governed only by the flow. Other deposits (like hydrates and wax) are dependent on the flow as well as thermal effects. It is generally accepted that wax formation is one of the most practically difficult deposits to deal with. The reason is that there is only one reliable way to remove wax, and that is by means of pigging (sending scraping devices through the pipeline that mechanically remove the wax). The problem with wax is that it grows slowly and by the time it is noticed that wax formation is occurring (pressure drop in the pipeline increases), it is almost always a problem that is too big to handle. This means that a lot of preventative pigging occurs, simply to avoid the situation where wax gets an opportunity to build up. Statoil report that the situation is made more complicated by the fact that wax formation is not fully understood and many current models are simply incorrect. As Statoil report *'This means that models can rarely be used to determine the pigging frequency, again leading to a large amount of (probably unnecessary) preventative pigging. These pigging operations are time consuming and expensive which can lead to a situation where production is no longer economical'*. The work reported in this case study on the rational model development and analysis of wax deposition on the interior walls of heated oil pipe lines has made significant impact on the understanding, and hence the potential resolution, of this significant issue.

The programme of research has involved two fundamental themes, namely:

Multiphase Pipe Line Flow: A rational mathematical model, based on fundamental hydraulic principles, has been developed to describe the two-layer hydraulic flow of gas and liquid in pipe lines. The co-current flow of gas and liquid in a circular pipe is of tremendous importance in the oil and nuclear industries. One significant feature which makes multiphase gas/liquid flow systems special is the presence of different flow regimes. Transport of the two phases can occur in the form of stratified flow, slug flow or dispersed flow depending upon the upstream inlet flow rates of each fluid phase. Statoil report that 'despite a large quantity of both experimental and theoretical research, focused on understanding and predicting the flow rate transition boundaries between these distinct flow regimes, there remain large holes in our understanding.' In particular, understanding and predicting the flow regime transition from uniform two-layer flow to two-layer slug flow is crucial to the efficient operation of gas/liquid transporting pipe lines in the oil and gas industries. Such pipe lines may operate over hundreds of kilometres, transporting gas and an associated thin liquid layer, from the source gas field to controlled distribution centres. The efficient operation of the pipe line flow over such large distances is of fundamental importance for the effectiveness, both economically and environmentally, of gas/oil transport.

This project has been successful in providing a rational theoretical framework to enable the prediction and control of slugging behaviour in gas/liquid pipe line flows, and the interpretation of experimental measurements and observational phenomena. The theory developed now forms an integrated part of the programme at the Statoil Research Centre, as a source of fundamental mechanistic understanding, to inform rational software model development and to assist in resolving practical issues relating to particular Statoil gas/oil pipeline networks in the field.

The theory has also enabled informed decisions to be made in relation to designing future experimental programmes relating to gas/oil pipe line transport. On a broader front, the theory has resolved the fundamental issues surrounding the origin of the transition phenomena for slug flow. It is now broadly accepted, as a consequence of this programme of work, that the transition phenomena is dissipative and hydraulic in origin, rather than of Kelvin-Helmholtz type. This understanding has been fundamental in shifting the focus of research in this area at Statoil, and has had a consequent fundamental impact on advances in this area, in terms of the design of more economically, energetically and environmentally favourable strategies for gas/oil pipeline delivery.

The work has led to a detailed report for Statoil (Nonlinear waves in two-layer hydraulic pipeline flows' Contract Report for the Statoil Research Centre (D J Needham, J Billingham, A C King) and a workshop ('Gas-Liquid Pipe-Line Flows' held at the Statoil Research Centre, Porsgrunn, Norway in March 2008, and supported fully by Statoil. Co-Chairmen – R M S M Schulkes*, D J Needham..

Attended by approximately 50 people, mainly from UK and Norway, including scientists from Statoil and University of Oslo) to discuss its implications, implementation and future development.

This work has contributed to the development by Statoil of an active slug control system in their Heidrum field in the Norwegian Sea, which has produced a more stable well stream flow into the first stage flow separator, leading to significant economic benefits. It is anticipated that the success of this active slug control system will lead to its implementation at other Statoil fields.

Pipe Line Deposit Control: A rational mathematical model, based on fundamental thermal transfer principles, has been developed to describe the formation and evolution of wax layers on the interior of pipes transporting heated oil. Up to the present, attempts at modelling these phenomena have had very little success, and have failed to predict even the basic qualitative features identified by carefully controlled experiments at Statoil Research Centre. This lack of success, together with the very significant implications of these phenomena to the petrochemical industry, motivated the establishment of this project with Statoil. There is consensus in the oil industry that wax deposition is governed by molecular diffusion whereby dissolved wax diffuses toward the pipe wall. Other deposition mechanisms have been suggested such as Brownian diffusion, gravity settling and shear dispersion. None of these mechanisms can be entirely discarded while at the same time there is still controversy about the mechanisms governing wax deposition since the diffusion-based model yields predictions that are qualitatively incorrect for certain important cases.

We have proposed an entirely different approach: that wax deposition is a phase change problem. The crystallisation of wax is an exothermic process, meaning that wax will only be formed there when heat, as a result of the crystallization process, can be removed. The growth of the wax layer will thus be governed by the balance of heat supplied by means of convection to the wax layer from the oil phase and heat removed from the wax layer by means of conduction. The problem that is obtained is a moving boundary problem of a generalised Stefan type.

The analysis of the model has led to predictions that are now qualitatively, and to a good degree quantitatively, in accord with the results of the experimental programme in place at the Statoil Research Centre. This agreement is very encouraging and had led Statoil to design further experimental programmes which are now informed by the predictions of this model. It is emerging from this that the model established in this case study will be developable by Statoil into a predictive tool which will considerably reduce the significant economic burden of the systematic pigging operations, which are currently in use as the only effective measure. This work has been documented in a report to Statoil ('The development of a wax layer on the interior wall of a circular pipe transporting heated oil' Contract report to Statoil AS (D J Needham, B T Johansson, T Reeve)).

In relation to both of the above projects, D J Needham has presented four research seminars on this work at the Statoil Research Centre. R M S M Schulkes* presented a research seminar on related problems of significance for Statoil, to the School of Mathematics, University of Birmingham. D J Needham has given an instructional workshop on implementation at the Statoil Research Centre.

As an overview, [redacted] has commented: *'Flow assurance is a vital area of technology in which a step by step approach is taken to achieve, improve and implement technology elements. Each step taken which contributes to our ability to extend the range of subsea transported solutions is of significant value. The reason is that more and more marginal reserves can be produced. This flow related and wax depositional work is thus an important contribution towards revitalising and extending oil production in the North Sea*. '

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

Corroboration of the impact described in this case study can be obtained from the Leader, Multiphase Flow Research and Development, TPD RD NDS, Statoil ASA,.