Imperial College London

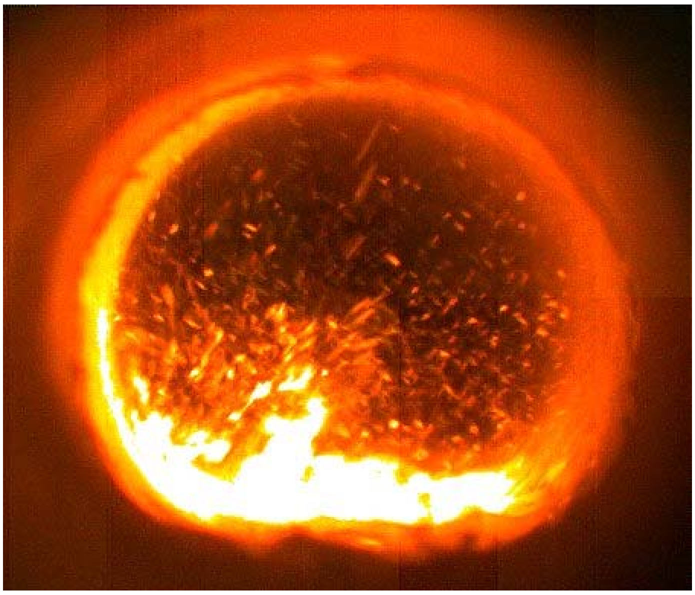
Joint Project on Complex and Transient Multiphase Flows and Flow Assurance

TMF5

PROSPECTUS

By

Geoffrey F. Hewitt, Programme Director (Imperial College)



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Joint Project on Complex and Transient Multiphase Flows and Flow Assurance (TMF5)

PROSPECTUS

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JOINT PROJECT ON COMPLEX AND TRANSIENT MULTIPHASE FLOWS AND FLOW ASSURANCE

TMF5

PROSPECTUS

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1. BACKGROUND

This Prospectus for a Joint Project on Complex and Transient Multiphase Flows and Flow Assurance (TMF5) describes a proposed research programme which has its roots in the extensive discussions with, and suggestions from, the industrial Sponsors of the current Joint Project on Transient Multiphase Flows and Flow Assurance (TMF4). The programme described here reflects extensive discussions with TMF4 Sponsors at the Autumn 2007, Spring 2008 and Autumn 2008 Sponsors meetings and also extensive discussions with individual and groups of Sponsors. TMF5 is the fifth successive TMF Project; the list of TMF projects (including TMF5) is as follows:

Managed Programme on Transient Multiphase Flows (TMF1): 1996-1999
Coordinated Project on Transient Multiphase Flow (TMF2): 1999-2002
Joint Project on Transient Multiphase Flows (TMF3): 2002-2006
Joint Project on Transient Multiphase Flow and Flow Assurance (TMF4); 2006-2009
Joint Project on Complex and Transient Multiphase Flows and Flow Assurance (TMF5): 2009-2012

The continuation of work in this generic area from one project to the next is an indication of the ongoing importance of the area to the oil and gas industry; however, the sub-projects forming the basis of each successive TMF project have been chosen to reflect the evolving industrial priorities. These priorities have been established throughout by intensive consultation with the industrial partners.

Two key features of the TMF projects have been as follows:

a) Though all the projects have been managed through Imperial College London, every effort has been made to involve other major Universities in the UK with expertise and equipment in the multiphase flow and related areas. For example, in TMF4, extensive work is being carried out at Cranfield University, Nottingham University and Bristol University. All of these Universities will be also involved in TMF5.

b) Funding from the UK Government has played a vital role in enabling the projects to address the industrial problems by providing support for study of the underlying engineering science. The principal UK Government funding has been provided through the Engineering and Physical Sciences Research Council (EPSRC).

From the start of the TMF projects, oil industry operating companies have contributed as Participants to a substantial Core Fund which, together with the contributions from EPSRC, has financed the work carried out. At the meeting of TMF sponsors held in April 2010, the oil industry operating companies agreed that membership of TMF5 should be extended to companies providing services to the operators at a cost of around one third that charged to the operators themselves. This revised version of the TMF5 Prospectus has been prepared to take account of this change.

In the earlier TMF projects (TMF1, TMF2 and TMF3), a proposal had been submitted to EPSRC at the beginning of the project covering all the work in the project. These (successful) EPSRC proposals had been focussed mainly on the support of research staff; the Core Fund had been used mainly for the non-staff costs of the projects (consumables, equipment, management, travel etc). Since the start of TMF4, a new approach was taken (compared to previous TMF projects) in which the Core Fund contributed by Participants was also used to support researchers (7 students and two Post-Doctoral Research Assistants). The approach taken regarding EPSRC proposals has been to make strategically-timed and separate proposals in specific Sub-Project areas. This has allowed a much more detailed and coherent case to be made for each topic.

Since new sponsors have access to all the data and information produced not only in the current TMF project but also that produced in the previous ones, it is important in this Prospectus to summarise the previous work and this is done in Section 2 below. A generic representation of the current state of the TMF projects is given in the chart shown here as Figure 1 and reference will be made to this chart in what follows. In Section 3, the current status of EPSRC projects spanning TMF4 and TMF5 is described and in Section 4 summaries are given of the work in each of the six sub-project areas in TMF5 and details are given of the related PhD projects proposed for funding under TMF5. Finally, in Section 5, details are given of the steps needed for oil and service companies to participate in the TMF5 project

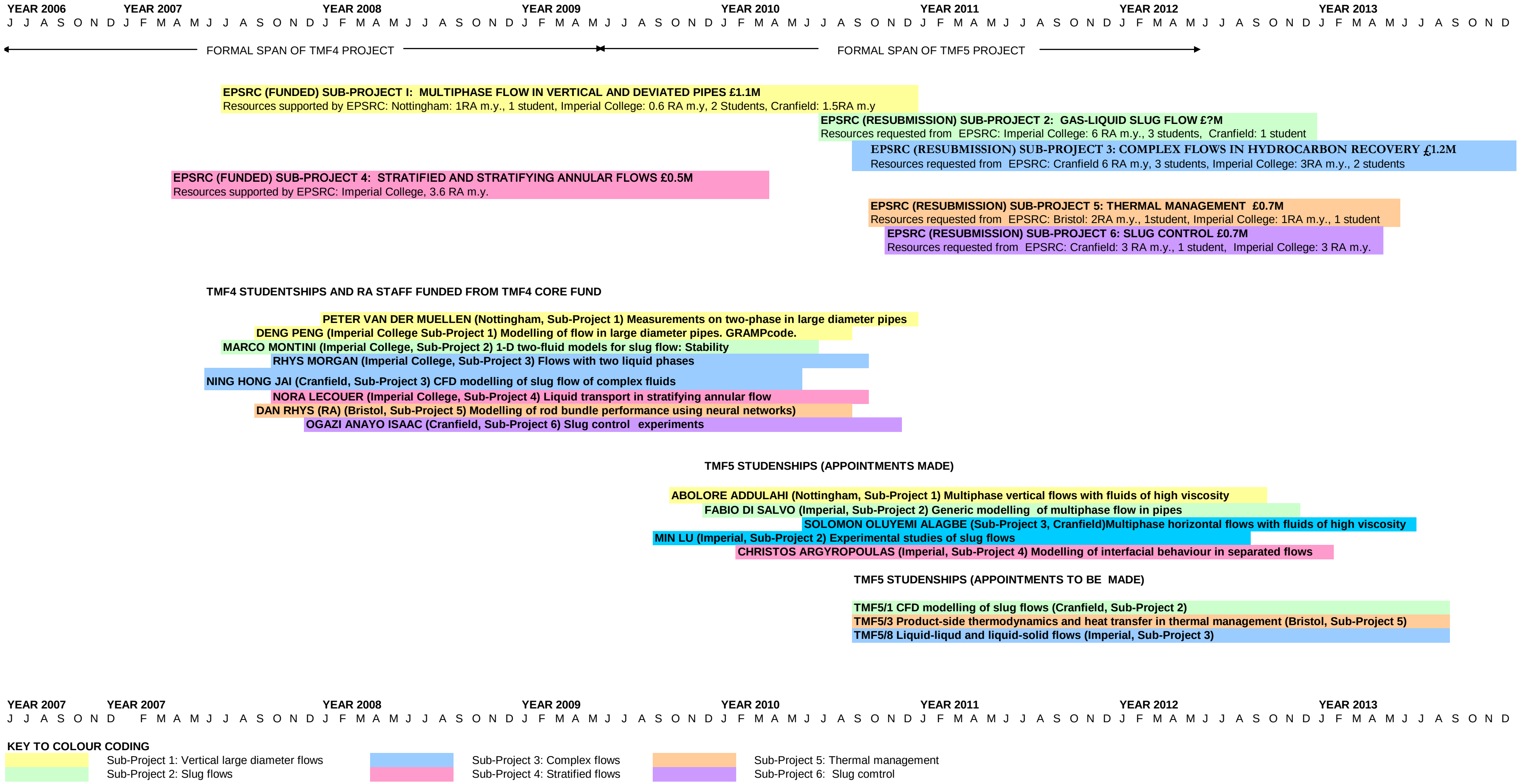

Figure 1: Current State of TMF Projects

2. THE PREVIOUS TMF PROJECTS

2.1 The Managed Programme on Transient Multiphase Flows (TMF1, 1996-1999)

The TMF1 project was jointly funded by the oil industry and its contractors and by the UK Engineering and Physical Sciences Research Council (EPSRC). The overall aim of the research was to advance the knowledge of transient multiphase phenomena, improve the coding of the available computer models and thus directly benefit the industry in its quest to improve operability, safety and reduction in capital costs. The TMF1 Programme was organised in six Projects as follows:

Project 1: Transient Three-Phase Flows (Imperial College Chemical Engineering). This work was focussed on obtaining a wide range of new data on steady state and transient water-oil-gas three-phase flows on the WASP facility at Imperial College. Development of new instrumentation based on dual-energy gamma densitometry (with single beam, triple beam and traversing beam devices being used) allowed a wide range of data to be obtained for horizontal, downhill and uphill/downhill flows, including transients.

Project 2: Phase Interactions in Transient Stratified Flow (Imperial College Chemical Engineering). This work was concerned with simultaneous measurement of the key parameters in stratified flows in both steady state and transient conditions. These parameters included local velocities in the gas and the liquid (using hot wire and hot film probes), wall shear stress in the gas and liquid regions (using hot film probes), interfacial structure (using multiple twin-wire probes), pressure drop using rapid response transducers, holdup using gamma densitometry and visualisation using special high pressure visualisation methods, including axial view video. The experiments were compared with closure models used in predictive codes and, in the case of transients, with the code predictions. Perhaps the most important finding was that transients cannot be adequately predicted using closure laws based on steady state data.

Project 3: Slug Growth and Collapse in the Flow of Gas Liquid Mixtures in Pipes (Imperial College, Chemical Engineering and Mechanical Engineering). Large sets of new experimental data were produced for both steady state and transient flows in 1.5° downhill inclined and downhill-uphill (V-section) configurations, both sets of data being obtained on the WASP facility. The application of the one-dimensional two-fluid model to the slug flow case using an in-house code (TRIOMPH) as a test bed was investigated. It was shown that, given a small enough mesh size, the one-dimensional two-fluid model *could* predict the formation and translation of slugs. It is believed that this work demonstrated for the first time that such predictions were feasible.

Project 4: Flexible Risers Severe Slugging (Cranfield University). A wide-ranging series of experiments were carried out in a 10 m high S-shaped riser over a range of pressures (2, 4 and 7 bara) and a range of buffer vessel volumes. Comparisons were made between six selected data sets and the predictions from commercial codes. The agreement between code predictions and data was not good; perhaps equally significant, the agreement between the selected codes was also not good, indicating the great uncertainties involved in such prediction methods.

Project 5 Numerical Simulation of Multiphase Flow (Cranfield University). Here, the main objective was to develop new numerical methods for application in the solution of the drift flux and multi-fluid (two-fluid and three-fluid) models for multiphase flow. A new (three-layer) model was also developed for three-phase stratified flow. It was demonstrated that enormous savings in computing resources was possible using grid adaptivity or, more likely, an ability to calculate at more detail with the same resources.

Project 6: Transient Mass Transfer in Co-existing Hydrocarbon Liquid and Gas Phases in Flowing Systems (Imperial College, Chemical Engineering). The main objective of this project was to gain better information on mass transfer phenomena in hydrocarbon pipeline transport systems. In computer codes for predicting both steady state and transient flows in pipelines, it is the common practice to assume *local equilibrium* between the respective phases. A new test facility was constructed in which stratified propane/methane mixture flows were set up in a 25.4 mm (1 inch) diameter, 2.4 m long horizontal tube. A series of transient tests were carried out with various changes of pressure level in the gas phase, with a constant liquid flow rate and with a range of gas flow rates; the time for equilibration was determined. It was concluded that departures from equilibrium may not be too significant in steady flows in very long (tens of kilometres) pipelines but that departures from equilibrium may affect local phenomena in crucial regions.

2.2 The Co-ordinated Project on Transient Multiphase Flows (TMF2, 1999-2002)

As in the case of TMF1, the TMF2 programme was again funded jointly by the oil industry and its contractors and by the UK Engineering and Physical Sciences Research Council (EPSRC). The objectives of the TMF2 Project were similar to those of TMF1, with an increased range of topics and University participation.

Work in the TMF2 Project was carried out under of 7 Sub-Projects as follows:

Sub-Project A: Modelling Bases (Cranfield University, Imperial College Mechanical Engineering, Nottingham University, Imperial College Chemical Engineering). Here, the work at Cranfield on numerical algorithms continued and a new code framework (EMAPS) was developed which supported automatic adaptivity. At Imperial College, the one-dimensional two-fluid model studies of slug flow were continued within the context of the TRIOMPH code. A particular focus was on taking account of gas entrainment in the slug body based on the formulation of a scalar-transport equation for the volume-fraction of entrained-bubbles in the liquid. This equation yields the distribution of entrained gas within the liquid slug and predictions of slug flow behaviour which take account of gas entrainment were shown to give better agreement with experimental behaviour. Under this Sub-Project, Nottingham and Cranfield Universities collaborated in obtaining new data for two-phase flow in combining junctions and in using two-fluid models (embodied in the EMAPS code) to predict this data respectively. In the experiments, it was shown that upstream propagation of waves from the T-junction was possible in some circumstances.

Sub-Project B: Three-Phase Flow (Imperial College Chemical Engineering, Cranfield University, Imperial College Mechanical Engineering). In the work at Imperial College (Chemical Engineering), new data were generated for steady state and transient three-phase stratified and slug flows. By using conditional sampling of the output from dual energy gamma densitometers, it is possible to obtain the distribution of the three phases within the slugs. This shows that the gas phase is concentrated towards the top of the slugs rather than being well mixed as is often assumed. At Cranfield, work continued on the development of multi-layer models for three-phase stratified flow; for instance, a *four-layer* model (water, oil-water mixture, oil and gas, in ascending order from the bottom to the top of the pipe) was formulated and calibrated against data obtained at Imperial College. In the work at Imperial College (Mechanical Engineering), a novel approach was followed to simplify the model for three-phase flow into one that closely resembles the two-fluid model, yet enabling the prediction of three-phase flow. This is achieved by combining the two sets of equations for the two liquid phases into one set for both liquid components. In order to account for the relative motion of these liquid phases, a new scalar transport equation for the phase fraction of one liquid component in the liquid phase was formulated. The new model showed good agreement with data for three-phase slug flow.

Sub-Project C: Tube Bundles (Imperial College Chemical Engineering, Bristol University). Tube bundles, in which a pipe carrying the hydrocarbon product is passed through a sleeve pipe which also carries a heating fluid, are common in offshore operations. Experiments on a water filled simulated four-tube bundle were carried out at Imperial College and used to validate CFD calculations on the natural convective heat transfer between the tubes carried out at Bristol. A spreadsheet model for interpolating the CFD calculations and predicting the performance of the whole bundle system was also developed at Bristol.

Sub-Project D: Transport Behaviour of Particulate Solid Constituents (Cambridge University). This Sub-Project was concerned with the estimation of the fluid velocities necessary for the transport along a pipeline of sand particles present in the (multiphase) streams from wells. Measurements were made of the critical velocity for initiation of transport of sand particles in single-phase water flow, two-phase stratified flow and two-phase slug flow over a range of flow rates. Stand-alone spreadsheet programs were developed which allow the conditions in which particulate material is transported to be estimated.

Sub-Project E: Transient Hydrodynamic Loading (Cambridge University, Cranfield University). If slug flows occur in pipelines, then transient hydrodynamic loadings may be generated in fittings such as bends and junctions. The aim of this Sub-Project was to address the problem of predicting the magnitude and frequency of such transient (and potentially destructive) forces. Measurements were made at Cambridge (and in larger scale equipment at Cranfield) of the bend forces in slug flow and these measurements were used to validate models for the prediction of the forces which were embodied into a spreadsheet model.

Sub-Project F: Flexible Risers (Cranfield University). This work extended the studies done under Project 4 of TMF1 to the case of three-phase (oil-water-gas) flows. Problems addressed included that of the mechanism of gas penetration at the riser base. It was clearly demonstrated that modelling of severe slugging depended critically on the inclusion of the complete system (i.e. not just the test section) into the model.

Sub-Project G: Coupled Heat and Mass Transfer Effects (Imperial College Chemical Engineering). This project continued the studies carried out under Project 6 of TMF1. The experimental facility was modified to allow transients in *composition* rather than pressure, as had been used in TMF1. Again, it was concluded that the equilibrium assumption was reasonable for calculations on long pipelines.

2.3 Joint Project on Transient Multiphase Flows (TMF3, 2002-2006)

As with TMF1 and TMF2, the work under TMF3 was supported by a single overall grant from EPSRC and by funds contributed by a group of oil industry sponsors. Work in the TMF3 project was carried out under 9 Sub-Projects as follows:

Sub-Project I: Multi-fluid Modelling (Cranfield University, Imperial College Mechanical Engineering). Here the work at Cranfield was focussed on the development of numerical methods and at Imperial College Mechanical Engineering on improvement of one-dimensional models for slug flows.

Sub-Project II: Slug Tracking (*Imperial College Chemical Engineering).* In slug tracking, the evolution and motion of individual "objects" (slugs or large waves) are tracked along the channel. In this work the basic formulation of the slug tracking model was derived from first principles, ensuring consistency in local and global mass and momentum balances. Good agreement between the model and data obtained at Imperial College was demonstrated.

Sub-Project III: Large Diameter Risers (*Nottingham University).* With fields being developed in ever increasing water depths, the importance of large diameter vertical and steeply inclined riser systems is increasing. This provides severe challenges to the methodologies for predicting flow regime, phase fractions (holdups) and pressure gradient. This is because the flow regimes (and hence the other parameters) may be very different in large diameter pipes. In the TMF3 studies, new data were obtained which confirmed this different behaviour.

Sub-Project IV: Thermal Management (*Bristol University, Imperial College Chemical Engineering).* Here, work carried out on the prediction of gas-filled multi-tube bundles at Bristol University was validated by large scale experiments at Imperial College. A new design approach using neural networks was developed.

Sub-Project V: Three-Phase Flows (*Imperial College Chemical and Mechanical Engineering, Cranfield University)*. Here, new measurements on three-phase flows were carried out using multiple gamma densitometers and X-ray tomography by Imperial College Chemical Engineering and special adaptations of two fluid model were carried out to incorporate the relative motion of the two liquid phases by Imperial College Mechanical Engineering. At Cranfield University, a three-fluid model was developed taking account of mixing between the water, oil and gas.

Sub-Project VI: Junction Flows (*Nottingham University).* In this Sub-Project, new measurements were made on air water flows in combining junctions and on air-kerosene flows in dividing horizontal T-junctions. In combining slug flows, a new phenomenon was found in which slugs could be broken up into a series of shorter slug ("caravan slugs").

Sub-Project VII: Flexible Risers (Cranfield University). This work included the generation of much new data on two- and three-phase flows in flexible risers and modelling of such flows, with particular reference to severe slugging. A new phenomenon observed was that of liquid-liquid separation in the riser.

Sub-Project VIII: Non-Newtonian Flows (*Imperial College Chemical Engineering, Cranfield University)*. This was in the form of an assessment study which surveyed the occurrence of non-Newtonian flows in hydrocarbon recovery and paved the way for research in this area in TMF4. The product from the work was an assessment report for use in industry.

Sub-Project IX: Active Control of Slug Flows (*Imperial College Chemical Engineering, Cranfield University).* This was also an assessment study and surveyed the various methods used for active control of slug flow. Again, a reference report was produced for industrial use and the foundations laid for work in this area in TMF4.

Sub-Project X: Technology transfer (Cranfield University). Under a grant from the UK Department of Industry, work was carried out on making TMF software (and specifically the EMAPS two-fluid model code developed at Cranfield) available to the TMF industrial partners in source code form.

2.4 Joint Project on Transient Multiphase Flow and Flow Assurance (TMF4, 2006-2009)

As was mentioned in Section 1 above, for TMF4, sponsors funds have been used to fund a cadre of PhD students. In parallel, applications for additional funding have been made and are being made to EPSRC. The EPSRC funding is being requested in specific technical areas rather than for the TMF4 project as a whole. The EPSRC funded projects will span the time frames of the TMF4 and TMF5 projects as indicated in Figure 1. Further information on these projects is given in Section 3 below.

The TMF4 project has been organised into 6 Sub-Projects as listed below; in each area, a Sub-Project Coordinator (indicated in parenthesis in the list) has been appointed:

Sub-Project 1: **Multiphase flow in vertical and deviated pipes** (Barry Azzopardi, Nottingham University)
Sub-Project 2: **Slug flow** (Raad Issa, Imperial College)
Sub-Project 3: **Modelling of complex flows** (Chris Thompson, Cranfield University)
Sub-Project 4: **Interfacial development and behaviour in stratified flow** (Peter Spelt, Imperial College)
Sub-Project 5: **Thermal management** (Joe Quarini, Bristol University)
Sub-Project 6: **Slug control** (Hoi Yeung, Cranfield University)

The staff funded by the sponsors' contributions have been allocated to the above Sub-Project areas. 7 Postgraduate Students and 1 Research Assistant have been appointed to the TMF4 team as listed in Figure 1. As will be seen from this Figure, the completion dates for the students are generally in 2010, depending on when they were appointed. The students and the RA appointed and funded with TMF4 funds are as follows:

Peter van der Meulen (Nottingham University, Sub-Project 1, Supervisor Professor Barry Azzopardi) whose work is focussed on experimental measurements on the Nottingham large diameter vertical flow rig using new advanced instrumentation such as wire mesh probes.

Deng Peng (Imperial College Chemical Engineering, Sub-Project 1, Supervisors Professors Omar Matar and Geoff Hewitt) who is working on modelling of flows in large diameter vertical pipes and, in particular, on modelling the transition region between bubble flow and churn flow. There is evidence that the slug regime does not exist with pipes of diameter larger than around 100 mm.

Marco Montini (Imperial College Mechanical Engineering, Sub-Project 2, Supervisor Dr. Raad Issa) who is working on the stability of two-fluid models for slug flow and the associated ill-posedness issues.

Rhys Morgan (Imperial College Chemical Engineering, Sub-Project 3, Supervisor Professor Geoff Hewitt) whose focus is on flows with two liquid phases, carrying out Laser Induced Fluorescence studies on liquid-liquid flow and on larger scale measurements on three-phase flows using X-ray tomography etc. He is also working on the modelling of flows with two liquid phases.

Ninghong Jai (Cranfield University, Sub-Project 3, Supervisor Professor Chris Thompson) whose work is on CFD modelling of slug flows. Using such modelling, the evolution of stratified flow into slug flow can be captured and the approach has been used to investigate the influence of non-Newtonian fluid behaviour on the evolution process.

Nora Lecoeur (Imperial College Chemical Engineering, Sub-Project 4, Supervisors Dr. Peter Spelt and Professor Geoff Hewitt) who is working on stratified and stratifying annular flow. Experiments are being carried out on interface behaviour and on droplet transport using advanced optical methods, and in particular axial view photography. The project includes modelling work in which droplet motion is being studied using CFD. An investigation is being pursued of the influence of the type of turbulence model (RANS, LES) on the predictions.

Dan Rhys (RA) (Bristol University, Sub-Project 5, Supervisor Professor Joe Quarini) who has been extending the methods developed for horizontal tube bundles to the case of inclined or vertical bundles. For the horizontal case, the convective flows are essentially two-dimensional; for an inclined or vertical bundle, the flows become three-dimensional and prediction of bundle behaviour is more difficult (though still feasible using the CFD/neural network methods developed in TMF2 and TMF3.

Isaac Ogazi Anayo (Cranfield University, Sub-Project 6, Supervisors Drs. Hoi Yeung and Yi Cao) who is working on slug control problems doing both modelling work and also carrying experiments on the major facility at Cranfield.

The success of the scheme of financing students from the funds contributed by industrial partners has led to the continuation of the scheme for TMF5. More details about the plans for PhD projects for TMF5 are given in Section 4 below.

3. EPSRC PROJECTS SPANNING TMF4 AND TMF5

In the context of all the TMF projects, proposals have been submitted to the Engineering and Physical Sciences Research Council (EPSRC) for additional funding. In the case of TMF1, TMF2 and TMF3, a single EPSRC proposal was submitted at the beginning of the project to provide support to cover the range of Sub-Projects planned; in each case, the requested funding was granted. Generally speaking, the EPSRC funds were used mainly to support staff and the industrial funds were used mainly to cover equipment and related costs and management. For TMF4, a different approach is being followed in which the funds from industry are being used mainly to support staff (students and management). Bearing in mind the considerable investment in equipment made in earlier TMF projects, the appointment of a cadre of students (see Section 2.4 above) guarantees a viable programme in each of the six Sub-Project areas listed in Section 2.4. However, in addition, proposals are being submitted to EPSRC which are focussed on each of these six Sub-Project areas.

It should be stressed that these submissions to EPSRC are in their so-called “responsive mode” – i.e. they have to compete with the many other proposals submitted from UK Universities. Only a relatively small proportion of proposals submitted are funded. There are essentially two phases in the consideration of proposals by EPSRC; the first is to submit the proposals for peer review. If these peer reviews are sufficiently strong, then the proposals are considered by a ranking panel which places the proposals in order of priority for funding. The highest ranked proposals are provided with funds, the cut off point depending on the amount of funding available.

The situation with respect to EPSRC proposals which span the time periods of TMF4 and TMF5 is summarised in Figure 1. All proposals submitted so far have reached the ranking panel stage. The situation on TMF proposals can be summarised under three headings as follows:

a) Proposals which have been submitted to EPSRC and which received funding.

b) Proposals which did not receive funding on first application to EPSRC but which will be resubmitted at the times indicated in Figure 1 (note that EPSRC requires a six-month waiting time before resubmission).

Proposals falling into each of these two categories are summarised in Sections 3.1 and 3.2 respectively.

3.1 EPSRC proposals spanning TMF4 and TMF5 which have received funding

Two major proposals which have been submitted to EPSRC and which have been funded are summarised as follows:

3.1.1 *Multiphase flows in vertical and deviated pipes (Sub-Project 1, £1.1M, 3.1 RA man years, 3 project students).* This project deals with the important question of prediction of multiphase flows in large diameter vertical and deviated pipes. Such pipes are typified by the risers which bring multiphase fluids from deep sub-sea fields to the surface. Most studies of multiphase flows have been with relatively small diameter tubes (typically 25-75 mm) but risers for deep sea fields are generally much larger (typically 300 mm diameter). The limited amount of data available shows that the flow patterns in larger pipes may be quite different and that, within a given flow pattern, the detailed phenomena may also be different. For instance, there are reasons to believe that slug flow of the normal type (with liquid slugs separated by Taylor bubbles of classical shape) may not exist in large pipes. This EPSRC project aims to address this area by carrying out work under the following Work Packages:

Work Package 1: Experimental studies of flows in 127 mm pipes (Nottingham University). Here, the objective is to obtain new data over a wide range of flow conditions and fluid physical properties using the new Nottingham large diameter facility and applying advanced experimental techniques. Major purchases of equipment are being pursued under this Work Package, including an advanced wire-mesh electrode system and a multi-pin film thickness measurement system. Experiments are planned with the test section in the vertical orientation and with it deviated from the vertical by 5° and 10°. Air or sulphur hexafluoride will be employed as the gas phases and water or silicone oil as the liquid phases. This combination of fluids will enable gas densities over a range 2.4-24 kg/m3, surface tensions from 0.025-0.072 N/m to be tested. Liquid superficial velocities of 0.001-1.5 m/s and gas superficial velocities of 0.01-20 m/s will be used.

Work Package 2: Air-water flow experiments in a 250 mm vertical pipe (Cranfield University). This study (employing an existing low-pressure facility at Cranfield) is concentrating on the bubble and slug-like flow regimes studying both the overall behaviour of such flows and also the behaviour of individual large bubbles. The rig is being operated at conditions ranging from bubble to annular flow and measurements made of both global and local parameters. The global parameters include pressure drop and void fraction mean values and time series. By cross correlation of the outputs from void fraction sensors, the velocities of structures present in the flow can be determined. The local parameters measured include interface velocities and bubble sizes (measured using conductance and/or optical probes). It is also proposed to study the stability of spherical cap bubbles by introducing a large bubble of known size into a water flow in the vertical large diameter (250 mm) test section and studying its subsequent behaviour using high speed photography and local conductance and/or optical probes.

*Work Package 3: Annulus experiments on churn-like and annular flows (Imperial College)***.** Here, churn and annular flows will be studied in annulus geometries which allow liquid films with large peripheral widths whilst minimising the requirements for gas flow compared with tubular systems. Wave behaviour is a key factor in both churn flow and annular flow; the objective will be to study the formation and transport of these waves. For annular flows, above a certain peripheral width of the liquid film, the span-wise coherence of the disturbance waves may break down and a range of peripheral widths will be studied to determine when this breakdown will occur.

Work Package 4: Application of interface tracking methods (Imperial College). Here, interface tracking methods (and specifically level sets) are being applied to the study of the behaviour of large bubbles in two-phase flow. The first part of the study concerns the behaviour of individual large bubbles released into a liquid in a vertical large diameter pipe. Initial numerical experiments will assume a large bubbles rising in static liquid; the stability of the bubble (wave formation on the bubble surface, bubble skirt breakup into smaller bubbles) will be investigated as will the influence of initial bubble shape. The calculations will then be repeated for the case where there is liquid flow. In the second part of the study, the interaction of large bubbles with bubble clouds will be investigated; interface tracking methods will be used for the large bubbles and the smaller bubbles would be represented by Lagrangian tracking.

It should be emphasized that work in the above Work Packages is strongly linked to the PhD projects of Peter van der Meulen (Nottingham University) and Deng Peng (Imperial College Chemical Engineering) which are described in Section 2.4 above.

3.1.2 ***Stratified and stratifying annular flows (Sub-Project 4, £0.5M, 3.6 RA man years).*** Many of the multiphase flows encountered in hydrocarbon production are in the stratified regime or the stratifying annular regime. In stratified flow, the liquid phase flows in a smooth or wavy layer at the bottom of the pipe with the gas flowing above it. In stratifying annular flow there is a combination of a stratified layer at the bottom of the pipe coupled with a thin liquid film around the rest of the circumference. In both cases, entrainment of droplets may occur and may represent an important mechanism for transporting the liquid to the top of tube. Such flows are immensely important in hydrocarbon recovery.

The overall aim of the work in this project is to develop fundamental insights into the physical processes that determine friction and droplet entrainment in turbulent gas flow over a liquid layer in pipes and channels, through a coordinated programme of numerical simulation and supporting experiments, supplemented by analytical efforts. The ways in which the outcomes of the work may best be exploited in industrial calculation methodologies will also be assessed.

In the analytical work being pursued under this EPSRC-funded project, the objective is to predict wave formation, growth and breakup using a combination of turbulence models for the gas phase coupled with level-set-type models for the interfacial behaviour. This work extends the previous Imperial College numerical modelling studies of wave formation in laminar-laminar stratified flows. The gas phase turbulence is being modelled using models of various levels of detail (including Direct Numerical Simulation, DNS and Large Eddy Simulation, LES). The aim is to gain an understanding of the complex turbulence/interface interaction processes which govern the system behaviour.

This work is closely related to the PhD project of Nora Lecoeur, which is supported from the industrial core funds and which was summarised in Section 2.4 above. This work includes measurements of wave properties (including entrainment phenomena) for comparison with the analytical predictions and also CFD studies of droplet behaviour.

3.2 EPSRC proposals which did not receive funding on first application but which will be resubmitted at the times indicated in Figure 1

Four of the proposals submitted to EPSRC which (despite having a good response from the reviewers) did not receive funding are now awaiting resubmission. The planned resubmission dates are indicated in Figure 1. These proposals are as follows:

3.2.1 ***Gas-liquid slug flow (Sub-Project 2, £0.7M, 6 RA man years, 4 project students).*** Slug flow is arguably the most important regime in produced hydrocarbon transport. The prediction of pressure drop and liquid holdup in slug flow is important in the design of pipeline systems. Also, the intermittent nature of slug flow gives, in itself, special problems including separation difficulties and the generation of potentially damaging transient forces. For these reasons, work on slug flow has formed an important part of the TMF projects from the beginning. This proposal is intended to extend and build on the earlier work to reflect the availability of new methods and tools. In the resubmission of this proposal, the following Work Packages are envisaged:

Work Package 1: Basic analytical models for 3D slug flows. Here, the numerical 1D interface tracking studies carried out in Sub-Project I of TMF3 will be extended to 2D and 3D simulations with the objective of resolving the short wave disturbances and much more of the detail surrounding the final stages of nonlinear wave evolution that precede slug formation.

Work Package 2: Three-dimensional predictions of slug flow using commercial CFD packages. A whole body of work has been carried out with empirical and one-dimensional two-fluid models. These models depend on closure relationships derived from empirical data. However, some of the vital local information (such as local flow structure and wall and interfacial shear stresses) are not easily obtainable from experimental measurements. Fortunately, recent developments in Computational Multi-phase Fluid Dynamics (CMFD) and matching advances in computer hardware give encouragement to the view that it may be possible to capture important multi-dimensional features of slug flows by these means. It is proposed to use CMFD to carry out extensive calculations on slug flows covering a wide range of gas-liquid flows and pipe inclination angles. Calculations using CMFD would be extended to longer pipe lengths to attempt to capture the development of the slug flow in the region beyond slug initiation. Data would be extracted from the output which could be used within a 1D modelling framework. It should be noted that work on CFD modelling of slug flows is being pursued already in the TMF4 Core-Funded PhD project of Ninghong Jai summarised in Section 2.4 above.

Work package 3: One-dimensional (multi-fluid) modelling. For industrial applications, the one-dimensional model is currently the only practical tool to predict multiphase flow in pipelines; the lengths of these flow lines prohibit the use of multi-dimensional computational techniques which would require enormous computer resources. In this approach, the starting point is the formulation of a one-dimensional two-fluid model, which is used to describe the evolution of the flow as a function of time and distance. Remarkably, previous work in the TMF projects has shown that this approach is able to predict both steady state and transient slug flows in a convincing way. The work proposed in this work package would be focussed on application of the 1D modelling strategy to pipes of all inclinations, to the extension of the methodology to the wide range of fluid properties encountered in hydrocarbon production, and to improvement of the friction closure laws. It should be noted that work on some aspects of 1D modelling are being pursued already in the TMF4 Core-Funded PhD project of Marco Montini summarised in Section 2.4 above.

Work Package 4: Experimental studies of slug flows. The initiation of slugs and their subsequent evolution are highly complex and still poorly understood processes. Detailed visualisation of these processes is difficult since the evolution takes place over a relatively long distance and the velocity of the slug and its precursors varies with position. It is proposed to obtain improved visualisation by using a moving high-speed video camera system, the position of the camera being controlled by a feedback system. Work is also proposed on measurement of the rate of gas entrainment at slug fronts. The rate of entrainment is difficult to measure objectively and different techniques give widely differing results. The aim is to use new systems which more closely represent the real case. It should be noted that work on some of these experimental aspects is proceeding under separate funding and is being reported to TMF sponsors.

3.2.2 ***Complex flows in hydrocarbon recovery (Sub-Project 3, £1.2M, 9 RA man years, 5 project students).*** In considering actual flows in hydrocarbon recovery processes, the fact has to be faced that real hydrocarbon production fluids are often very complex and difficult. They can have complex structures and extremely high viscosities (heavy oils) and they can be non-Newtonian in nature (as exemplified by waxy crudes which exhibit yield stress behaviour and by slurries). This proposal addresses these problems. The proposed work is split into two themes, namely gas-liquid flow with high viscosity and non-Newtonian liquids (Theme 1) and flows with two liquid phases (Theme 2). The proposed Work Packages are as follows:

Theme 1, Work Package 1: Experimental studies of multiphase flows with high viscosity and non-Newtonian liquids). In the experiments proposed, the existing large scale three phase flow facility at Cranfield would be employed. This facility has a test section of 100 mm (4 inch) diameter. As the facility was designed for relatively low viscosity oil, extra gas liquid separation and temperature control systems will need to be designed and incorporated. It is intended that the work would include measurements on gas-liquid flows with high viscosity Newtonian and shear-thinning fluids. Measurement methods would include the use of a high speed gamma densitometer (at 250 Hz), a dual-modality Electrical Resistance Tomography (ERT) and an Electrical Capacitance Tomography (ECT) system.

Theme 1, Work Package 2: Modelling studies of multiphase flows with high viscosity and non-Newtonian liquids. Here, the main focus will be on the application of Computational Multi-phase Fluid Dynamics (CMFD) to predict these flows. This Work Package is strongly linked to the TMF4 PhD project of Ninghong Jai which was summarised in Section 2.4 above.

Theme 2, Work Package 1: Experimental studies of flows with two liquid phases. In this work package, advanced experimental techniques will be applied to the study of mixing processes in flows with two liquid phases. Basically, two existing facilities at Imperial College London (namely the WASP facility for three-phase flows and the TOWER facility for liquid-liquid two-phase flows) will be employed to explore these processes. In the experiments proposed for the WASP rig, the main experimental tool will be the X-ray tomography system which uses two X-ray sources directed at right angles through the test section, the beams being modulated between hard and soft using filter wheels. New investment to increase the speed of data acquisition from this system has been requested. In the TOWER facility, liquid-liquid flows will be studied with particular reference to the evaluation of mixing processes between a heavier aqueous phase at the bottom of the pipe and a lighter organic phase at the top. The refractive indices of the two fluids will be matched so that the laser induced fluorescence (LIF) technique can be employed to study the mixing processes. Work in this area is already being pursued as part o the TMF4 PhD project of Rhys Morgan which was summarised in Section 2.4 above.

Theme 2: Work Package 2: Detailed studies of liquid-liquid-solid flows. In many practical applications, systems with flows of an oil phase and an aqueous phase, solid particles (sand, wax particles, hydrates) may be present and this, of course, greatly complicates the flow. At Imperial College, it is proposed to study such flows using the LIF technique. At low particle concentrations, discrimination of the solid phase will be investigated using opaque solid particles and viewing them against a background of the LIF field with the two liquid phases having fluorescence induced with different colours. At high particle concentrations, the aim would be to use transparent solid particles and to match their refractive index to those of the two liquid phases. The particles could then be visualised by fluorescence.

Theme 2: Work Package 3: Gas-liquid-liquid flows with high viscosity oil and water. This Work Package is essentially an extension of the work under Theme 1, Work Package 1 to flows with two liquid phases, i.e. water and a high viscosity and/or non-Newtonian liquid. The same apparatus will be employed but the instrumentation extended to measure independently the fractions of the two liquid phases. The dual modality tomography system is essential to capture the behaviour of the three phases.

*Theme 2, Work Package 4: Multi-dimensional modelling of flows with two-liquid phases***.** Flows with two liquid phases can be categorised under the general headings of *fully-dispersed, fully-separated,* and *partially-dispersed/separated.* In a generic sense, such flows are not susceptible to accurate modelling because of the complex processes of droplet/turbulence interactions and the coupled processes of droplet transport, coalescence and break-up. Nevertheless, CMFD has been increasingly used for calculations on multi-phase systems of this type and has been found to give useful information and insights into the systems which could not be obtained by other means. The intention will be to use both Eulerian-Eulerian and Volume of Fluid (VOF) methods in this work. The Eulerian-Eulerian approach will be used for calculations on liquid-liquid and liquid-liquid-solid flows in horizontal pipes and the VOF method will be used for calculations of stratified and slug flows with two liquid phases.

Theme 2: Work Package 5: Development of improved models to represent liquid-liquid mixing in the context of one-dimensional modelling of flow with two liquid phases. At present, the vast majority of engineering calculations of flows in hydrocarbon recovery systems are carried out using the one-dimensional two-fluid model. However, the flows are often (and indeed usually) of three phases, namely oil, water and gas. The objective of the work proposed in this Work Package is to develop methodologies for representing such flows within the one-dimensional two-fluid model framework. In order to develop appropriate closure relations necessary to close the proposed 1D model, data and results from the other Work Packages, and especially the multi-dimensional simulations proposed in Theme 2, Work Package 4 will be utilised.

3.2.3 ***Thermal management (Sub-Project 5, £0.7M, 3 RA man years, 2 project students).*** In a typical sub-sea field, the product from the wells flows along the sea bed in subsea pipelines which terminate in risers which lead the fluids to a separation system (typically mounted on a platform or ship). The product emerges from the well at a relatively high temperature but then cools in the cold subsea environment. Hence, it is usually necessary to maintain hydrocarbon production streams at a sufficiently high temperature, during pipeline and riser transport, to prevent the deposition of wax, asphaltenes and hydrates. Often, "active heating" is used in which the product pipe is mounted in a tube bundle which also contains heating pipes containing hot water. The design of sub-sea bundles has been a major topic of work in TMF2 and TMF3. There, the focus was on horizontal tube bundles but an increasing problem for the oil industry is that the products have to pass through risers whose length has been increasing significantly as the sea depths at which hydrocarbon recovery is undertaken have increased. Thus, there is a need for thermal management of such risers and one solution is to use tube bundles. Such riser bundles are either vertical or steeply inclined and this presents a significant modelling challenge. This EPSRC proposal addresses the following Work Packages:

Work Package 1: Design and Methodologies for Horizontal Tube Bundle Systems: Technology Transfer. Here, the objective is to transfer the technology generated in earlier TMF projects to industry via an automated framework to carry out performance and design calculations for any given horizontal tube bundle system.

Work Package 2: Transient Behaviour of Tube Bundles. It is axiomatic, of course, that tube bundle systems must be started up and also, at some stages, closed down. The behaviour during start up and shut down is of vital importance and any anomalous behaviour which occurs in these circumstances may affect the long-term performance of the bundle. It is proposed, therefore, to conduct CFD calculations on transient performance in start up and shut down.

Work Package 3: Inclined and Vertical Tube Bundles. As in the case of the previous work on horizontal bundles, the approach to inclined bundles will be to generate a wide range of data using CFD and to interpret this data for design using a neural network method. The CFD method will be validated by carrying out full-scale experiments on inclined bundles. It should be noted that work on inclined bundles has already started in the project being carried out by Dan Rhys under the TMF4 industrial Core Funding as summarised in Section 2.4 above.

Work Package 4: Advanced Insulation Systems. There have been remarkable advances in insulation materials in recent years. These materials are already finding their way into the domestic market and there is considerable potential for their use in thermal management for production pipelines. However, it should be realised that the sub-sea environment is an extremely hostile one. What would happen if the insulation were cracked? What would happen if the insulation became filled with seawater rather than air? This Work Package would focus on developing models for heat transport in such materials and carrying out complementary experimental work.

3.2.4 ***Slug control (Sub-Project 6, £0.7M, 6 RA man years, 1 project student).*** Slug flow is a naturally occurring regime in pipelines carrying gas-liquid mixtures, typified by those bringing hydrocarbon products from the sea bed to a processing facility such as a platform. Though it is vital to have models for such *hydrodynamic* slug flows the consequences of the intermittency of the flow *per se* are not too serious since the slugs are relative short (typically 10-30 pipe diameters) and these can easily be handled by separation equipment. Unfortunately, however, another manifestation of slugging (namely *severe slugging*) has proved to be extremely troublesome in hydrocarbon production from sub-sea sources. Severe slugging can be induced in interactions between flow lines and risers, by changes in pipeline terrain or by some types of operational transient. Severe slugging has been studied extensively in previous TMF projects (see summaries above). A new finding in the work on riser severe slugging was that choking of the riser outlet can prevent severe slugging but that severe slugging can reappear if the riser outlet is over-choked. Though a number of systems for the control of severe slugging are now in operation in hydrocarbon recovery operations, there is a clear case for a much more detailed study based on fundamental control theory. The source of this requirement is the fact that severe slugging control systems often have an adverse effect on production and the selection and design of an optimal system presents special difficulties. The proposed work is structured into Task Groups as follows:

Task Group 1: Upgrading of equipment. Here, the tasks are focussed on further development of the major severe slugging facility at Cranfield University. The length of the flowline will be increased to 100 m, the liquid feed system modified and an improved control system installed.

Task Group 2: Experimental studies on severe slug generation and initiation. This Task Group will provide basic understanding of severe slug generation mechanism, and the mechanism of over-choking induced slugging will be investigated. A crucial issue in severe slugging is the mechanism by which, at the location of an increase in pipe inclination the gas and liquid phases separate in such a way that only the liquid phase passes up the downstream (rising) section whilst the gas phase remains in the upstream section. All models of severe slugging assume that such a separation will occur but the separation process is not understood. The work will include basic measurements on, and visualisation of the separation process. Work in this Task Group will also include studies of operational and over-choking induced severe slugs.

Task Group 3: Modelling for slug control. The main purposes of the proposed modelling study are 1) to perform theoretical analysis for fundamental understanding of severe slugging, 2) to provide a mean for real-time model-based slugging control, 3) to facilitate control algorithm scale-up. This work will be carried out at Imperial College where, in the Centre for Process Systems Engineering (CPSE) a generic solver environment (gPROMS) has been developed for transient process simulation. The first step will be to generate source-riser-separator performance and control models within the gPROMS environment; these models would then be validated with experiments carried out on the modified equipment at Cranfield University.

Task Group 4: Slugging Index to detect slug flow. Task Group 4 develops a slugging index (*SI*). The *SI* is a novel proposal of the project giving a real time metric for slug characterisation. Its uses are (i) as a signal analysis tool in an oil platform to give early warning of the onset of slugging, and (ii) as a feedback signal in the new model-based controller. The *SI* will give early warning of the onset of slugging by analysis of the measurements from the top of the riser, e.g. pressure at the top of the riser.

Task Group 5: Slug controller design. Task Group 5 undertakes analysis and design of a controller. Physical understanding of the process is crucial in choosing the configuration of the controller, while selection of the settings for the selected actuators is posed as a model predictive control problem. The main objective is to maximize flow rate.

Task Group 6: Controller verification and testing. The outcome of Task Group 6 will be a demonstration of a model-based slug flow controller for the Cranfield facility. The demonstration together with the know-how gained in developing the model will provide a starting point for future work towards large-scale implementation.

4. THE TMF5 PROJECT

For the TMF5 Project, the same Sub-Project structure has been maintained as in TMF4, namely as follows, with the Sub-Project Coordinator being named in parenthesis:

- Sub-Project 1: **Multiphase flow in vertical and deviated pipes** (Barry Azzopardi, Nottingham University)
- Sub-Project 2: **Slug flow** (Raad Issa, Imperial College)
- Sub-Project 3: **Modelling of complex flows** (Chris Thompson, Cranfield University)
- Sub-Project 4: **Interfacial development and behaviour in stratified flow** (Peter Spelt, Imperial College)
- Sub-Project 5: **Thermal management** (Joe Quarini, Bristol University)
- Sub-Project 6: **Slug control** (Hoi Yeung, Cranfield University)

Funding in each of the Sub-Project Areas has been obtained or is being sought from EPSRC as detailed in Section 3 above. Also, in all areas apart from Sub-Project 6, there will be direct funding of PhD projects from the Core Fund contributed by industrial participants. This follows the policy started in TMF4 (see Section 2.4 above). TMF5 will start on June 1st, 2009 and the aim will be to recruit a new cadre of students to start in the summer/autumn of 2009. It is intended that a total of 8 such studentships will be implemented. The topics chosen for the TMF5 PhD projects emerged from a prioritisation process which started with the specification of possible projects by industrial participants[1]. The plans for each Sub-Project area in TMF5 are summarised as follows:

Sub-Project 1: Multiphase flow in vertical and deviated pipes (Sub-Project Coordinator: Barry Azzopardi, Nottingham University). The area of flows in vertical and deviated pipes is one of increasing importance in hydrocarbon recovery. This reflects the increasing use of large diameter risers in deep sea systems. There is a real dearth of data on large diameter vertical and deviated pipes and wells. Flow patterns, and therefore closure laws, may be very different in large diameter conduits and there are severe doubts about whether models based on the data for smaller diameter pipes can realistically be applied to these cases. Work was started in this area in TMF3, is continuing in TMF4 and will continue in TMF5. Major funding (£1.5 M) for this area was secured from EPSRC in January 2008 and work under this funding will continue until December 2010, thus spanning the TMF4 and TMF5 periods. The contents of this EPSRC-funded work are summarised in Section 3.1.1 above. Support for 3 Project Students and for 3.1 years of a postdoctoral Research Assistant (RA) is available from this EPSRC grant in addition to extensive funding for new measuring equipment. There are also two ongoing PhD projects in this area funded from TMF4 core funds (i.e. those of Peter van der Meulen, Nottingham and Deng Peng, Imperial College – see Section 2.4 above). A new PhD project will be started in TMF5 reflecting the increased interest in systems involving liquids of high viscosity. The specification of this project is as follows:

PhD Project: Multiphase vertical flows with fluids of high viscosity *(Abolore Addulahi, Nottingham University, Supervisor Professor Barry Azzopardi).* Most research work on multiphase flows has been carried out with low viscosity liquids (typically water which has a viscosity of around 0.001 Pa s, 1 cP). However, the oil industry has to handle liquids which have much higher viscosities; liquids in this category with viscosities up to 0.2 Pa s (200 cP) are often classified as *high viscosity liquids* whereas those with viscosities over 0.2 Pa s are often classified as *very high viscosity liquids.* Based on very strong support for this topic from TMF Participant Companies, it has been decided to implement two TMF5 PhD projects in this area - the one described here for vertical flows and also one on horizontal flows (see Sub-Project 3 below).

The project described here will be carried out at Nottingham University under the direction of Professor B. J. Azzopardi. The main focus will be on carrying out experiments in channels of various diameters (up to 125 mm). Existing equipment at Nottingham will be adapted for these experiments. Candidate liquid phases for use in the experiments will be dead crude oil or sugar solutions.

The prime aim of the experiments will be to evaluate the effect of high viscosity on the flow patterns (determined by phase distribution measurements), pressure gradient and liquid holdup. Since the liquids used may be opaque, it is intended to investigate flow structure with the aid of Electrical Capacitance Tomography (ECT). The results from this technique can be processed to yield mean holdup values in addition to giving more detailed information on phase distribution.

The design and operation of facilities for study of multiphase flows with liquids with high viscosity presents formidable difficulties. These relate to the separation of the phases after they leave the test section. The bubbles in such systems tend to be very small and separate only slowly from the viscous liquid. The best solution seems to be to operate the facility in a "once-through" mode. Thus, the liquid phase would be pumped (probably using a mono-pump) from a holding tank into the test section inlet where the gas phase is also added. After passing through the test section, the two-phase mixture would be fed to a separator vessel where it is left for a (probably long) period of time to allow the separation of the bubbles. Thus, the maximum run time is that corresponding to that for emptying the holding tank. After the bubbles have

[1] A separate note was prepared and distributed to TMF4 sponsors which gives details of the marks cast and of the selection process undertaken.

separated in the separation tank, the liquid is pumped back to the holding tank and the cycle can be repeated.

The data from these experiments will be compared with existing correlations for estimating flow pattern, holdup and pressure gradient. It seems unlikely that these existing correlations will fit the new data involving a high viscosity liquid and modifications will be proposed where appropriate to take account of the viscosity effects. Also, the application of phenomenological models, which take explicit account of the flow structure, will be investigated.

Sub-Project 2: Slug flow (Sub-Project Coordinator: Raad Issa, Imperial College). Slug flows are of great importance and, despite many years of work in the area (including work in the TMF projects) there are still difficulties in prediction. The direct calculation of slug behaviour by applying the two-fluid model at a high level of discretisation ("slug capturing") has been developed under the TMF projects and has proved very promising and the commercialisation of these methods is now being pursued. However, more detailed information is required on many aspects of slug flow; this includes investigation of the precise slug initiation mechanisms, the study of the effects of pipe inclination and the measurement of gas entrainment at slug fronts. This more detailed information can increasingly be gleaned from CFD calculations but experiments are still required. In addition to continued modelling work in this area in the form of a TMF4 PhD project by Marco Montini (see Section 2.4), it is planned to resubmit an EPSRC proposal for funding in the Spring of 2009. This £0.7 M proposal will involve requests for funding for 4 Project Students and for 6 Research Assistant man years of effort. Further details are given in Section 3.2.1 above. There is very strong ongoing support from TMF participating companies for continued work on slug flow and this was reflected in high votes for PhD projects in the area for TMF5. Three PhD projects on slug flow resulted and these are described in what follows:

PhD Project: CFD modelling of slug flows *(Student to be appointed, Cranfield University, Supervisor Professor Chris Thompson).* The use of CFD (Computational Fluid Dynamics) methods (applied via the use of major commercial CFD codes such as CFX, FLUENT and STAR-CD) has always had a place in the TMF and associated projects. In the past, CFD has been used to address relatively simple cases, but this usage was nevertheless crucial in answering some very basic questions about slug flows (see for instance the paper by Ujang et al, Multiphase Science and Technology, Vol. 20. pp. 25-79, 2008). With the increasing power of computers and with the increasing sophistication of codes capable of carrying detailed interface tracking in multiphase flow systems, it is clear that CFD is now capable of calculating situations which are much more complex than those addressed in the earlier work. Specifically, it is now possible to make full calculations of developing slug flows, showing how the interfacial waves in stratified flow develop into slugs and how these slugs subsequently travel along the test section, entraining gas at their front. Calculations of this type have been carried out at Cranfield University under the TMF4 programme and have certainly demonstrated a *prima facie* case that such methods are now giving physically realistic results. Cases have been performed where gross features of the flow (such as slug frequency) have been correctly predicted and there are indications that more detailed features are also captured. The work proposed under the PhD project presented here is aimed at exploiting and developing this technology.

The first step in this project will be to carry out sets of calculations relating to existing TMF data sets on developing slug flow. The aim will be to examine the methods not only from the point of view of the (already established) qualitative capability, but also on the predictions of quantitative data such as the evolution of slug frequency and velocity with length along the tube. New data generated in the experimental activities for this Sub-Project on slug flow in inclined tubes and on gas entrainment at the slug front will also form part of this validation base (see below). Of course, the strength of this technology is that it calculates 3D transient information so it is much less dependent on ad hoc correlations. We will look at details of the flow such as PDF and PSD distributions and spatial distributions and compare these with experimental results (both video and tomographic).

The goal is to develop and verify more accurate and more widely applicable models of two-phase flow. We can use the 3D results to enhance 1D models of the type currently used for a range of engineering calculations. However, 3D models can also be used to study flows in more complex geometries and we will perform some computations to understand the feasibility of calculating the effects on the flow of (slight) changes in geometry – the narrowing of pipes caused by sand or wax deposition and flow interaction with pipe bends and junctions.

Most CFD calculations are made with RANS models such as the *k-ε* model. This approach will be used in much of the work described above. However, more advanced turbulence models (such as Reynolds Stress models and Large Eddy Simulation (LES) methods) are increasingly viable and are now available in the major commercial CFD codes. The effect of choice of turbulence model will be explored by carrying out a limited range of calculations with advanced models and the results will be compared with those obtained using simpler RANS methods. These effects are comparatively small; however some numerical experiments have already been performed which show that under some situations of industrial significance the higher-order turbulence models give results which are more accurate (Jayanti et al. Int. J. Multiphase Flow, 1990).

An appealing feature of CFD predictions is that they can often be used to address issues which it would be expensive (and sometimes even impossible) to investigate experimentally. An area which falls into this category is that of *non-Newtonian Flows.* Such flows are important for the oil industry and there is a dearth of systematic work in the area, particularly on the effects of turbulence in non-Newtonian flows which, for multiphase systems, are not well understood. Non-Newtonian flows are also important in start-up and shut-down procedures. In TMF4, a start has been made on predicting slug behaviour in non-Newtonian flows using CFD methods and it is the intention to extend this work under the PhD project presented here. Systematic studies of the effect of deviation from Newtonian will be performed.

PhD Project: ***Experimental studies of slug flows*** *(Min Lu, Imperial College, Supervisor Professor Geoff Hewitt).* The study of two-phase (gas-liquid) and three-phase (gas-liquid-liquid) slug flows has been an important part of the TMF projects since TMF1. A large amount of experimental data has been collected on developing, fully developed and transient slug flows and this has served as a basis for an extensive modelling effort which now allows many of the characteristics of such flows to be predicted. However, TMF Participant Companies indicated a strong interest in having slug flow studies continue on both the modelling and experimental fronts within the TMF5 project. Specific areas which were identified as requiring more experimental work (and which would be addressed in this three year PhD study) will include the following:

(1) *Slug Initiation*. The mechanism and process of slug initiation is of crucial importance in predicting slug flows. Slug initiation in two-phase in horizontal pipes is being studied in TMF4 using a high speed camera mounted on a moving platform whose motion is computer-controlled to track the initiation and development process. However, many industrial applications involve inclined pipes and/or three-phase (liquid-liquid-gas) flows; slug initiation and development processes in such cases is not well understood and will be one of the subjects of this PhD project. Here the advanced instrumentation (gamma densitometry, X-ray tomography, moving frame high speed video etc) will be applied.

(2) *Entrainment in Slugs*. The entrainment of the gas phase at the slug front is an important factor in modelling slug flows. Also its effect on slug density is important in deciding loading issues. Previous measurements of entrainment rate have given conflicting results, these being dependant on the measurement method used. As part of TMF4, a new technique has been developed to determine entrainment rate at the slug front in a situation much more representative of actual two-phase slug flows; briefly, this involves setting up a two-phase stratifying flow and then injecting a liquid slug to pass over the initial stratified layer. The gas entrainment rate can be deduced from the slug propagation velocity. Promising results have been obtained using this method for 32 mm pipes and the technique is now being pursued for studies on the 79 mm test section of the Imperial

College WASP facility. Within this TMF5 PhD project, the intention will be to apply this technique to the case of three-phase flows. Attention would also be given to the study of the detailed void distribution near the slug front and to the behaviour (including breakup and coalescence) of the entrained gas bubbles as they pass through the slug body. Though the data obtained would be incorporated into correlations which can be used in modelling codes, detailed modelling of the entrainment processes would also be pursued.

(3) *Behaviour of slugs in inclined pipes and in pipes with changes of inclination*. In the TMF projects so far, there has been little work on slug flow in inclined pipes. Many complexities arise when the pipe is inclined ("bubble turning" for downwards flow, flow reversal in the film region for upwards flow being examples). In industrial practice, changes in inclination occur and slug flow proceeding from a pipe run at one angle of inclination to a pipe run at another angle would naturally undergo significant changes in characteristics. Another case is one where significant pipe curvature exists. In the PhD project described here, the aim will be to study the effects of pipe inclination and the effects of changes in inclination for both two-phase (air-water and oil-water) and three-phase flows, again using the wide gamut of instrumentation now available on the WASP facility.

PhD Project: Generic modelling of multiphase flows in pipes *(Fabio de Salvo, Imperial College, Supervisor Dr. Raad Issa).* One of the most important outcomes of the TMF programme has been the development of one-dimensional two-fluid models which are applied in a sufficiently detailed way that they are capable of capturing the features of the initiation and evolution of slugs in horizontal and near-horizontal flows (*slug capturing*). The models have been shown to be capable of predicting the data for two-phase slug flows with encouraging accuracy and have also been adapted to the prediction of three-phase flows. These models have been made available through TMF. Furthermore, work is now proceeding outside TMF to make the models available commercially through computer codes developed from the original Imperial College TRIOMPH code. There is significant support for maintaining the momentum on these generic one-dimensional approaches and the PhD project proposed here reflects this support.

A prime objective of the work in this project will be to extend the generic one-dimensional models to flows in tubes inclined at angles covering the full range from horizontal to vertical. Though this seems a simple extension, difficulties occur because of the fundamental ill-posedness of the one-dimensional two fluid models. These difficulties can be overcome for much of the parameter space for horizontal flows if account is taken of the gravity-induced pressure difference between the gas and liquid phases. However, there are difficulties in achieving well-posed solutions with vertical and inclined pipes. What are needed are practical methods for resolving these issues and the aim will be to explore a number of such approaches taking into account of experimental evidence and also evidence from three-dimensional CFD calculations. There is already a significant body of such evidence available within the TMF project and elsewhere but the work will benefit from new evidence which will be generated under the other TMF5 PhD projects in slug flow described above. Account has to be taken of the fact that the precursor to slug flow in horizontal pipes is stratified flow whereas in vertical flows, the precursor would be bubbly flow. At some angle of inclination, the dominant precursor regime will change. Another specific difficulty in vertical and inclined flows is that of intermittent flow reversal; thus, in the Taylor bubble in vertical slug flow, the liquid around the bubble may be flowing downwards. Incorporating these effects into the framework of one-dimensional modelling is clearly challenging, but a number of ways of meeting these challenges exist. Coupled with these special problems is the need to apply appropriate closure relationships; the bases of the closure laws for inclined flows are not well established. It is in this area where the use of CFD modelling as an investigative tool is expected to be particularly valuable.

Sub-Project 3: Modelling of complex flows (Sub-Project Coordinator: Chris Thompson, Cranfield University). In most studies of multiphase flows, the emphasis has been on multiphase flows of relatively simple fluids; this has in itself been challenging enough. However, the reality has to be faced that real hydrocarbon production fluids are often very complex and difficult. They can have complex structures and extremely high viscosities (heavy oils) they can be non-Newtonian in nature (as exemplified by waxy crudes, which exhibit a yield stress behaviour, and by slurries). Furthermore, the actual structure of flows with two liquid phases (liquid-liquid and liquid-liquid-gas) is only poorly understood and this forms a barrier to better prediction. The Sub-Project 3 work area aims to rectify these deficiencies by carrying out a broad programme of research. Within the TMF5 timeframe, it is proposed to submit to EPSRC a major (£1.2M) research proposal for work on complex flows; a summary of this proposal is given in Section 3.2.2 above. This proposal will request funding for 9 years of Research Assistant effort and for 5 Project Students. In addition, there are two TMF4 Core-Funded students working in the area (namely Rhys Morgan and Ninghong Jai - see Section 2.4 above). In the interaction with TMF participants on the core funded TMF5 sub-projects, the following 2 projects emerged as being appropriate for funding:

PhD Project: ***Multiphase horizontal flows with fluids of high viscosity*** *(Soloman Oluyemi Alagbe, Cranfield University, Supervisor Dr. Hoi Yeung).* The oil industry has a strong interest in fluids of *high* and *very high* viscosity. This was reflected in the votes of Participants on the TMF5 PhD project proposals. In view of the perceived importance of the topic, it was decided to include two projects in this area, the one described here on horizontal flow and the one described (under Sub-Project 1 above) on vertical flow. It will be possible to carry out this work by using an existing facility at Cranfield University. This facility has a 4 inch (100 mm) transparent tubular test section which is in the form of a 20 m long straight section followed by a 180^0 bend followed by a 20 m return line of the same diameter. The rig can operate with high viscosity liquids (liquids of 70 cP and 250 cP viscosity have already been employed). The liquids used so far have been selected on the basis of their transparency (allowing direct visualisation of the two phase flows, and in particular slug flows) but the rig is not restricted to such liquids. Instrumentation available on the facility includes capacitance probes, water-cut meters and a recently purchased dual-mode electrical tomography system (ECT and ERT). Further instrumentation will be developed as part of this present project. As in the case of the vertical studies (Sub-Project 1), there is a significant challenge in separation of the efflux mixtures and a similar solution is to be applied here, namely to operate the facility in a *once-through* mode with the efflux being passed to a large tank in which the phases are allowed to separate over a long period. Thus, several hours of separation time may be needed between runs of several minutes.

The experimental work in this project will include comprehensive studies of the flows of air/high viscosity liquid flows in horizontal tubes and in inclined tubes with inclinations (upwards and downwards) up to 20^0. Data will be collected on flow pattern, pressure gradient and void fraction and on detailed parameters such as slug frequency and slug body holdup. The experiments would initially be on gas-liquid two-phase flows but would then be extended to three-phase (liquid-liquid-gas) flows by introducing a second liquid phase. The data generated would be compared with existing correlations, with one-dimensional multi-fluid models as implemented in earlier parts of the TMF programme and, as appropriate, with multi-dimensional CFD predictions.

A specific problem, which the Cranfield facility has been designed to address, is that of sand behaviour in high viscosity liquid and high viscosity liquid/gas systems. The behaviour of trace quantities of sand, and specifically the propensity of sand to settle and collect in pipelines is a matter of concern in many operating systems. If transparent liquids are employed, then sand motion (or lack of it) can be clearly observed in the Cranfield gas/high viscosity liquid flow facility. Observations of such sand transport will be made as part of the proposed work in this present project.

PhD Project: ***Liquid-liquid and liquid-solid flows*** *(Student to be appointed, Imperial College, Supervisors Professor Geoff Hewitt and Dr. Raad Issa).* Flows in which one phase is a liquid and the other phase is either another liquid or a suspended solid are common in hydrocarbon production systems and this was reflected in significant support for this area from TMF sponsors. Previous work in the TMF projects has addressed liquid-liquid flows to some extent but flows with a solid phase have not so far been covered. The PhD project proposed here addresses both experimental measurements on, and modelling of such systems with the aim being to promote a synergy between the experiments and models so as to achieve an optimum modelling strategy.

In the proposed experimental work, the tests will be based on the use of the Imperial College TOWER (Two-phase Oil Water Experimental Rig) facility. This rig has already been used extensively for studies of liquid-liquid flows and will be adapted to also allow study of liquid-solid flows. The key measurement technique used in this work will be Laser Induced Fluorescence (LIF). In applying this technique to liquid-liquid flows, the refractive indices of the two liquids are matched and one of the liquids has added to it a fluorescent dyestuff. When a pulsed laser sheet is passed through the mixture, an image is produced which shows the instantaneous position of the fluorescent phase. A video sequence of such images gives an indication of the interface motion and phase interaction. This technique has already been demonstrated in pilot systems (see Liu et al Chem. Eng. Sci. Vol. 61, pp 4007-4021 & 4022-4026, 2006) and is expected to yield a wealth of new information in the tests proposed here. The LIF technique will be complemented by other measurements such as pressure gradient and chordal mean phase fraction determination using gamma ray absorption. In applying the LIF technique to liquid-solid flows, the intention will be to use fluorescent transparent solid particles and to observe their distribution and motion in the illuminated plane. For small concentrations, scattering by particles between the illuminated plane and the video camera will probably be acceptable. However, for larger concentrations, matching of the refractive index of the liquid and solid phases will probably be necessary. The main outputs from the studies will be phase distribution data and information about phase mixing.

One of the most important outcomes of the TMF programme has been the development of one-dimensional two-fluid models which capture the main features of the flows. As part of the TMF3 and TMF4 projects, there has been a focus on the prediction of liquid-liquid flows. The flows were treated as consisting of two layers with an aqueous-continuous layer at the bottom of the pipe and an oil-continuous layer at the top. Oil drops are dispersed in the aqueous layer and water droplets are dispersed in the oil continuous layer. The model includes expressions for the interfacial entrainment and capture of droplets into and out of the respective continuous layers. In the modelling work proposed here, data from the experiments will be used to close the models so that they can operate continuously from fully dispersed to fully separated flows. Multidimensional CFD models will also be used to provide inputs and insights into the one-dimensional models.

In the modelling of liquid-solid systems, the main focus will be on multi-dimensional CFD predictions. Basically, these will be of two types, namely *Eulerian* models in which the liquid and solid phases are treated as interpenetrating continua and *Lagrangian* models in which the motion of the individual particles are tracked within the turbulent flow field. Again, the experimental data will be used to validate and develop these models.

Sub-Project 4: Interfacial development and behaviour in stratified flow: (Sub-Project Coordinator: Peter Spelt, Imperial College). Many of the multiphase flows encountered in production are in the stratified regime. This regime is in many ways even more complex than slug flow. The interface is usually covered by a complex pattern of waves which not only exerts a profound influence on the all-important interface friction but is also the source of droplet entrainment. In view of these complexities, it is perhaps not surprising that there are no satisfactory generic relationships for interface friction even in the steady state flow case. Another serious problem is that the steady state interface friction relationships, though used extensively in the transient flow prediction codes, are demonstrably inapplicable to the transient case. Further investigation of interface characteristics and friction is indicated, extending the work done in steady flows and obtaining more data on stratified flows. The phenomena associated with drop entrainment are notably poorly understood; droplet entrainment and deposition are crucial factors in governing pressure drop. Thus formation of a slowly draining film of oil at the top of the pipe as a result of droplet entrainment, transport and deposition can give huge increases in pressure drop.

An important problem for the oil industry is “top of line corrosion”; this can take several forms and is often addressed by adding a corrosion inhibitor to the liquid phase. However, for such additives to be effective the liquid phase containing the additive must wet the upper surface of the pipe; a liquid phase formed at this upper surface by condensation (for example water containing CO_2) would not be effective and may actually promote corrosion. Thus, entrainment and deposition processes are of paramount importance in this key problem. Furthermore, in the case of three-phase stratified/annular flow, the identity of the liquid which wets the top of the pipe is important in governing corrosion behaviour; there is practically no information available on this. A £0.5M EPSRC research project in this area was funded from March 2007 to February 2010 and thus spans the periods of TMF4 and TMF5. This project funds 3.6 years of Research Assistant effort, focussed on interfacial stability and entrainment. Further details of this work are given in Section 3.1.2 above. In addition, there is an ongoing TMF4 PhD project on stratifying annular flows (Nora Lecoeur - see section 2.4 above). The ongoing importance of stratified flows led the TMF participant companies to support strongly the inclusion of a new PhD project in the area in TMF5. This project is specified below.

PhD Project: Modelling of interfacial behaviour in separated flows *(Chistos Argyropoulas, Imperial College, Supervisor Dr. Peter Spelt).* The crucial issue in stratified flows is that of the formation and development of interfacial waves, this development including growth to block the tube in the initiation of slug flow and including wave breakup (for instance by ligament formation) in stratifying-annular flows. In the latter case, the droplets formed on the stratified layer may be transported to the upper part of the tube to form a liquid film there; such films may have a crucial role in inhibiting corrosion in this region. Early work on stratified flow in the TMF projects was focussed on the application of one-dimensional multi-fluid models. More recently, the emphasis has been on the development of more rigorous modelling approaches. The first issue that must be resolved is the prediction of parameter ranges for which stratified flow is unstable, and the determination of growth rates of small-amplitude waves on a liquid film. This is being achieved by following Orr-Sommerfeld-type of analyses. In previous work, the effect of the turbulence on such model results has been assumed to be merely through the difference in laminar and averaged turbulent gas velocity profiles. However, further changes occur due to Reynolds stresses. A further key issue here is the interaction between turbulence and interfacial waves, even for small-amplitude waves: turbulence in the gas is distorted as it is advected over the waves, and this alters the growth rate of the wave. Under the parallel EPSRC project on stratified flows, the focus has been on accounting for these effects in linear stability models in an approximate manner, on the development of accurate CFD methods that allow one to simulate droplet entrainment events under turbulent conditions.

In the PhD project presented here for TMF5, the aim will be to continue this modelling development work, primarily using the numerical methods developed under the parallel EPSRC project to simulate the propagation of large-amplitude waves on liquid layers and droplet entrainment events under turbulent conditions. In order to develop practical models for the rate of entrainment that are accurate for a range of flow parameters it is crucial to have the insight into the interaction between turbulent structures and large-amplitude waves and liquid ligaments right up to the point of entrainment.

Overall, this work theme has led to the generation of much deeper understandings of the key processes and this function will continue in TMF5.

Sub-Project 5: Thermal management (Sub-Project Coordinator: Joe Quarini, Bristol University). It is often necessary to maintain hydrocarbon production streams at a sufficiently high temperature, during pipeline transport, to prevent the deposit of waxes, asphaltenes and hydrates. Such deposition may lead to serious loss of production and, in extreme cases, to complete blockage of the pipes. Where temperature maintenance is not possible using insulation, *active* heating by hot water streams is often used in which *tube bundles* are constructed carrying the heating and production pipes. CFD prediction of the performance of such bundles, coupled with experimental validation, has formed an important part of the TMF2, TMF3 and TMF4 projects. The essence of the work is the prediction of natural convection heat transfer inside the complex cross-sectional geometry of the bundle. The work has focussed on horizontal and slightly inclined bundles and has led to a consistent methodology for prediction of such systems. Briefly, this methodology involves carrying out a matrix of CFD calculations to cover the likely range of tube surface temperatures encountered, the fitting of the resultant data for heat transfer coefficient using neural network techniques and the use of these fits within a spreadsheet programme to calculate temperature profiles along the bundle. In TMF4, priority has been given in the research activity in tackling the much more difficult problem of thermal management in vertical or highly inclined bundles. Whereas the heat transfer in the horizontal case could be treated as two-dimensional, three-dimensional effects are very much to the fore in the vertical/highly inclined case. However, this case is becoming ever more important as more and more deepwater fields are being developed; for these fields, thermal management of the very long vertical and highly inclined risers is of vital concern. In principle, natural circulation of the fluid between the tubes in the bundle in such cases could take place over the full length of the riser, a situation for which it would be difficult to do meaningful calculations. It seems more likely, however, that tube supports would divide the riser bundle into a series of separate zones which (though the convection is three-dimensional within each zone) could be calculated in a similar manner to that used for the horizontal bundles. Work in this area has been carried under TMF4 Core Funding by Dan Rhys (see Section 2.4 above). A £0.7M proposal for work in this area will be resubmitted to EPSRC in the summer of 2009. The contents of this proposal are summarised in Section 3.2.3. In the discussion of TMF5 PhD projects with TMF industrial Participants, it was agreed that some work should be done on the *product side* behaviour and this led to the formulation of the following TMF5 PhD Project:

PhD Project: Product-side thermodynamics and heat transfer in thermal management *(Student to be appointed, Bristol University, Supervisor Professor Joe Quarini).* So far, the focus of the work in this Sub-Project area has been on heat transfer between the fluid between the tubes in the bundle (typically water or nitrogen) and the pipes carrying the product and heating streams. This heat transfer is typically governed by a combination of natural convection and radiation and, as such, depends on the temperatures of all the surfaces at any given cross section. This highly complex situation has been effectively dealt with in the TMF projects by using *neural network* methods to interpolate a large body of CFD predictions (typically of the order of 1000) covering the expected range of surface temperatures and inclinations. In all the work so far, a relatively simple representation of the product side fluid behaviour has been adopted (typically assuming that it has a constant heat transfer coefficient and specific heat capacity). It was expected that methods developed would be used in conjunction with other in-house or commercial codes to predict system behaviour. However, though this approach is still valid, it has become clear that much more attention needs to be given to product side behaviour as shown by the industrial participants' strong support for such a focus in their suggestions for new TMF5 PhD projects.

Though some work will continue on bundle-side behaviour in the PhD project described here (for instance on counter-current flow systems where heated bundles operate in counter-current flow with the heated water passing down the bundle in a tube but returning to the surface through the (water-filled) bundle), the main emphasis will be on product side behaviour. The principal aspects addressed will be as follows:

(1) *Startup and heatup transients.* How does a pipe restart having being blocked and then reheated. Transient cases are being investigated in the current TMF project but this work needs to be extended to cover more details of the product side behaviour.

(2) *Thermal management in situations with Joule Thomson cooling.* Dealing with situations in which Joule Thomson (JT) cooling plays a significant role is increasingly important. An example is that of restart of a gas well. Upon restart, the gas at the top of the well is approximately seabed temperature (4 degrees C). The valve is cracked open across a pressure drop of 2000 psig to about 300 psig. This results in JT cooling of the gas as it flows across the valve. Meanwhile, warmer gas approaches the wellhead from deeper down the well, and, the pipeline starts to pressure up. Estimates of JT cooling are approximately 30 degrees C. This gives rise to questions concerning hydrate plug formation just downstream of the wellhead, how much inhibitor is needed, and the duration of the JT cooling (estimated to be on the order of 5-10 minutes). All these factors are strongly influenced by the nature of the thermal management systems. The objective will be to review the problem and devise means of dealing with it in the context of active thermal management systems.

(3) *Heat transfer to viscous fluids.* There are considerable difficulties in predicting heat transfer and associated flow behaviour of the extremely viscous fluids encountered in many oil industry applications. Thermal management is particularly important in such cases. However, there are problems in predicting the product side behaviour. Viscous heating may be significant and may totally change the (laminar) velocity profile. There is a dearth of adequate 1D CFD models for this case and the first aim will be develop better models which can be subsumed into thermal management methods.

Sub-Project 6: Slug control (Sub-Project Coordinator: Hoi Yeung, Cranfield University). The occurrence of severe slugging presents a major potential problem in the operation of hydrocarbon recovery systems. Classically, the problem has been addressed by having separators ("slug catchers") which are large enough to contain the largest conceivable slug. In recent years, there has been a growing tendency to tackle the severe slugging problem by using some form of control system. Following an Assessment Study as part of the TMF3 Project (see Section 2.3 above), work was started in TMF4 on investigating control systems; this involved both modelling and experimental work (the latter using the major severe slugging facility at Cranfield University). A Core Funded PhD project was started in this area and is ongoing (the student involved is Isaac Ogazi Anayo – see Section 2.4 above). This further work demonstrated the need for a much more fundamental treatment of the control theory involved and will be reflected in a £0.7M EPSRC proposal which is summarised in Section 3.2.4 above. This proposal requests funding for 6 years of Research Assistant effort and for a Project Student and will be submitted in the timeframe indicated in Figure 1. Thus, though this area was not prioritised for allocation of TMF5 Core Funding to support a further PhD project, it is intended to continue the work at a basic level.

5. PARTICIPATION IN TMF5

Companies are invited to participate as Sponsors of this Joint Project on Complex and Transient Multiphase Flow and Flow Assurance (TMF5). The ticket price for operating companies is £35,000 per annum for three years. For new operating company participants there is a one off £20,000 buy-in fee which covers access to the extensive research undertaken in the previous TMF programmes. Following the decision of Sponsors at the April 2010 Participants meeting, companies providing services to the operating companies (for instance contracting companies) may join as Sponsors at an annual fee of £12,000 with a one off £7,000 buy-in fee. For their contribution, Sponsors would be assured of a centrally-funded activity of around £1M over 3 years (assuming a similar participation to TMF4) in which 8 postgraduate students and a postdoctoral worker would be employed on the projects described in Section 4 above, all of which have been carefully selected, in consultation with TMF4 Sponsors to meet the needs of industry. In addition, funds are being requested on an ongoing basis from the UK Engineering and Physical Sciences Research Council (EPSRC) to support extended engineering science work in each of the Sub-Project areas listed in Section 4.

In each of the previous TMF programmes in-kind participation has been included from organisations that can offer added value input in lieu of the fees. Such participation requires agreement from the existing sponsors.

G. F. Hewitt, June 2nd, 2010