

FOULING IN HEAT EXCHANGERS OF CRUDE DISTILLATION UNITS

PART 1: PREVIOUS RESEARCH AND TRACK RECORD

Crude oil distillation accounts for a large fraction of the energy used in oil refining. Thus, attempts are conventionally made to recover the energy used by a sequence of heat exchangers, often called the “pre-heat train”. A typical crude pre-heat train is illustrated in Figure 1. Unfortunately, crude oil contains a variety of substances, which tend to deposit as fouling layers in the heat exchangers and this results in decreased energy recovery and requires increased energy input (via the furnace prior to the column as shown in Figure 1). In a typical (100,000 barrel/day) unit, a loss of only 1 K in inlet temperature to the furnace would result in a cost of US\$ 40,000 per annum in additional fuel charges. Pre-heat train fouling is estimated to cost around \$1.2 billion per annum in the US alone (IHS ESDU, 2000)¹. In addition, savings in the use of non-reusable fuel will result in the reduction of CO₂ emissions.

The importance of the crude oil fouling problem has led to a number of studies, focusing on parameters that govern rates of fouling, namely temperature, pressure, oil composition, salinity and fluid velocity. Whilst the results are useful, the mechanisms by which the fouling proceeds are not fully understood. For example, it is generally assumed that materials depositing on heat transfer surfaces are *asphaltene* derived. These are typically complex mixtures of polynuclear aromatic ring structures, with high heteroatom content; they carry most of the trace element content of the oil. However, it is apparent that only small fractions of the asphaltene content in crudes actually deposit on heat exchange surfaces and that this can be catalysed by other species.

Asphaltene precipitation (deposition) is a common problem in most aspects of the oil industry, including oil production, transportation, and processing. The present proposal addresses deposition in heat exchangers, where there is reason to expect that significant progress in fundamental understanding can be achieved. Such understanding can be applied to upstream problem areas, and because the oil industry is actively participating in the project (mainly through the technology transfer activities of IHS ESDU, see below), upstream involvement in the project will be sought.

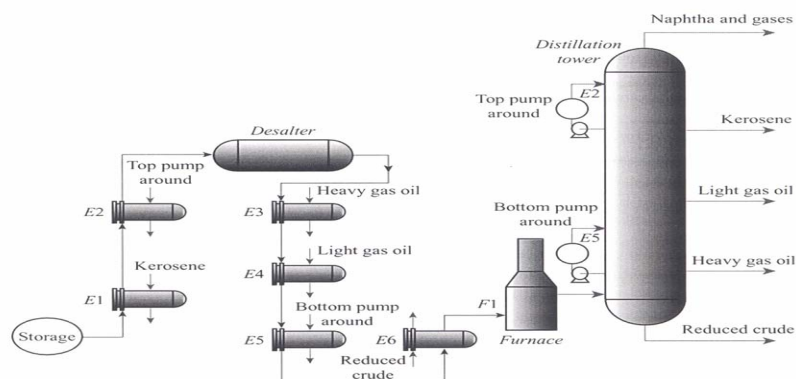


Figure 1: Schematic diagram of typical crude distillation unit (Panchal and Huang Fu, 1998²)

What is needed in pursuit of a solution to the problem is to advance the state of knowledge. The present proposal aims to provide a platform to (i) investigate fundamental parameters leading to deposition, (ii) provide a framework for predicting deposition and avoiding it by design and (iii) formulate methods for mitigation. Several types of input will be coordinated, addressing the chemical characterisation of deposits, the characterisation of the fouling process under controlled conditions and modelling across all scales from the molecular to the process unit. The proposal brings together researchers from Imperial College, Bath University, Cambridge University and IHS ESDU with the wide range of skills and backgrounds needed to attack the problem in new ways. An important feature of the proposal is to develop close links with the oil refining industry and their suppliers, building on an existing set of links developed by IHS ESDU through their Fouling Working Party.

Background expertise of the Investigators: In order to adopt a new line of attack for this crucial problem a team of world-class experts based in the UK has been assembled.

Imperial College London (Department of Chemical Engineering–CE)

The Principal Investigator Professor G.F.Hewitt FRS, FREng has worked for nearly 50 years on heat transfer and multiphase flow. He has published over 400 reports and papers and many books. Of particular relevance in the context of the present proposal is his long experience in process heat transfer; he founded the



Heat Transfer and Fluid Flow Service (HTFS) at the Harwell Laboratory in 1967 (which now has over 200 associated companies). He is Executive Editor of the Heat Exchanger Design Handbook and is the author (with G.L.Shires and T.R.Bott) of the book "Process Heat Transfer" published in 1994. Recently, he has been a principal author of a major guidance document on crude oil fouling (IHS ESDU, 2000).

The First Co-Investigator Professor S.M.Richardson, FREng is the Head of the Chemical Engineering Department at Imperial College, and has worked for over 30 years in the areas of fluid mechanics, heat transfer and thermodynamics. He has published over 300 reports and papers and two books. He has nearly 20 years experience of working on problems related to the oil industry. In particular, he is interested in all aspects of the safety of high-pressure hydrocarbon processes and is joint originator of the computer program BLOWDOWN, used world-wide to simulate the depressurisation of oil and gas installations.

The Second Co-Investigator Professor D.R.Dugwell has nearly 35 years research experience in energy and heat transfer related topics and has published over 100 papers and reports. He spent 10 years in industry where he was involved in the development and design of novel ceramic recuperators, and ceramic rotary regenerators, for heat recovery in the steel industry. He also modelled the complex heat transfer in continuous kilns used for firing refractory products. He has taught heat transfer to undergraduate students of Imperial College for 20 years. He has studied the thermal decomposition and characterisation of heavy hydrocarbon liquids, derived from coal, biomass and petroleum. He has collaborated widely with universities, research institutes and companies throughout the EU in more than 20 European-funded research projects; in addition, he has participated in many EPSRC and other UK-funded projects.

The Third Co-Investigator Professor G. Jackson is the co-ordinator of the Multiphase Fluid Systems Programme within CE at Imperial College. He is an editor of *Molecular Physics* and has published over 100 papers in internationally recognised journals. His main research aim is to provide a detailed understanding of complex fluids, liquid crystals and polymers at the molecular level, using recent developments in statistical mechanics and computer simulation. The focus is on the structural, dynamic and thermodynamic properties, with an emphasis on phase equilibria and phenomena that are difficult or impossible to study by experiment. One of key achievements of this work is the statistical associating fluid theory for potentials of variable range (SAFT-VR). The SAFT approach is superseding well-established chemical engineering equations of state; there are over 1000 citations to the original papers (Jackson appears in the ISI top 1% most cited chemist ranking since 1997). This work has put the UK at the leading edge of molecular based equation of state modelling of multi-component fluids.

The Fourth Co-Investigator Professor R. Kandiyoti is co-ordinator of the Energy Conversion Research Programme within CE at Imperial College. His research activities cover reactor design, thermochemical reactions of solid fuels, environmental aspects of energy conversion and the physical organic chemistry of complex hydrocarbon liquids. This work has led to over 250 publications. The 'tar group' working on the physical organic chemistry of complex hydrocarbon liquids has been active in method development for characterising heavy petroleum residues, asphaltenes and coal tars and pitches. In the past decade, this work has led to several significant advances and over 120 publications.

The Fifth Co-Investigator Professor C.J.Lawrence is Director of Research within CE at Imperial College. His research activities address the mechanics of fluids, multiphase systems and interfaces, with heat transfer, and mass transfer. He also works to understand the rheology, microstructure and processing of complex liquids and soft solids. In 2003 he was appointed to the Schlumberger – Royal Academy of Engineering Research Chair in Oilfield Process Engineering.

The Sixth Co-Investigator Professor P.F.Luckham is currently the Chairman of the Colloid and Surface Chemistry group of the Society of Chemical Industry and is a Council Member of the International Association of Colloid and Interface Scientists. His research interests are broad in the area of interfacial phenomena in liquid media, concentrating in two main themes of the rheology of disperse (multiphase) systems and atomic force microscopy as a means of determining the interactions between particles or molecules with other particles, surfaces or molecules. Recently he has had research contracts with various funding organizations to study numerous fundamental and applied problems, such as van der Waals force, the adhesion of carbon particles to paint films, the adsorption of oilfield polymers to mineral surfaces and the interactions between asthma drug particles in an inhaler. He has published over 150 papers in major international journals.

The Seventh Co-Investigator Dr. O.K.Matar is an Exxon-Mobil Fellow and Senior Lecturer. His research interests include the theoretical understanding and modelling of the dynamics of thin liquid films and slender jets and threads driven by various mechanisms such as Marangoni stresses, surface and bulk diffusion, gravitational, capillary, intermolecular forces and parametric forcing, placing particular emphasis on hydrodynamic instabilities and pattern formation, with industrial and biomedical applications. These include intensive processing, coating flow technology, surfactant replacement therapy, Marangoni drying, micro-fluidics and microelectronics. Dr. Matar is currently involved in EPSRC funded projects to study surfactant transport on



mucus films (GR/N34895), phase inversion in concentrated emulsions (GR/R54699/01) and thin film flow over a spinning disc reactor (SDR) (GR/R04676).

The Eighth Co-Investigator Dr. S.G.Kazarian is a Reader and co-ordinator of the Materials Engineering and Technology programme within CE in Imperial College. His research focuses on applications of vibrational spectroscopy to polymeric materials and supercritical fluids. Dr. Kazarian has published more than 80 articles in leading scientific journals. He has been an invited plenary speaker at international conferences and research seminars in Europe, the USA and Japan. He is the recipient and co-investigator of several EPSRC grants (GR/R57164, GR/N07035, GR/M58221, GR/S03942, GR/S57500). Recently his interests have broadened to include applications of spectroscopic imaging to heterogeneous materials. His research in this area has already been highlighted by scientific media as "technology solutions". In this work, it is proposed to realise the potential of FTIR Imaging for advanced analysis of asphaltene deposits to facilitate understanding of the mechanism of fouling processes.

The Ninth Co-Investigator Dr. A. Galindo is an EPSRC Advanced Research Fellow, an ExxonMobil Teaching Fellow, and a Lecturer in CE at Imperial College. Her interests are in the development of statistical mechanical approaches for complex systems. She leads a research group focusing on models for charged systems (concentrating in aqueous and mixed solvent electrolyte solutions, salting out behaviour, and the effect of charged surfactants in water+oil systems), the global (solid-liquid-gas) phase behaviour of chain-like (alkane-like) molecules, and of mixtures of liquid crystal molecules, and the study of near and supercritical phase behaviour in water solutions and in mixtures containing carbon dioxide. She has been working in close collaboration with Prof. Jackson in the development of the SAFT-VR approach.

The Tenth Co-Investigator Dr. Erich A. Müller is a recently appointed Reader within CE in Imperial College. His research focuses on the application of molecular simulation to problems of industrial interest. He has had experience with several grants and contracts with the Venezuelan oil industry, particularly in the area of molecular modelling of asphaltene aggregation and multiphase equilibria of complex crude oils. He has been involved in different aspects of the SAFT framework since 1991. He has published over 30 Journal articles and a textbook on thermodynamics and is member of the Editorial board of *Molecular Simulation*.

Bath University (Department of Chemical Engineering)

The Principal Investigator Professor B.D.Crittenden FREng has around 30 years experience of research in hydrocarbon fouling, selective adsorption, ceramic membranes, and environmental management. His research on hydrocarbon fouling commenced with the original idea that the problem could be described by a traditional chemical reaction model in which the overall rate was controlled by both mass transfer and kinetic effects. He has supervised 21 successful PhD's, published over 180 papers, reports and books overall, and he has worked extensively with industrial organisations such as BP and Cal Gavin on the crude oil fouling problem. Crittenden's particular interest centres around exploiting the understanding of how flow properties affect the overall fouling rate. To assist this, a high pressure, high temperature, recirculating flow, parallel test section, pilot-scale rig has been used to obtain substantial experimental data with a range of model fluids, crude oils and flow modification devices.

Cambridge University (Department of Chemical Engineering)

The Principal Investigator Dr. D.I. Wilson: is a Senior Lecturer at Cambridge, having moved there in 1994 after PhD work on hydrocarbon fouling with Profs. Paul Watkinson and Norman Epstein at the University of British Columbia. He has considerable experience in design, operation and commissioning of fouling test units and on modelling and chemical analysis. Since moving to Cambridge he has worked on data-based studies of crude oil fouling using refinery and pilot plant data, from data reconciliation of individual heat exchangers to large scale optimisation of refinery cleaning and retrofits. Recently he has worked with IHS ESDU on the development of the 'threshold modelling' approach to mitigate refinery fouling, which is receiving much attention. He has active collaborations on fouling with UBC, Shell, Exxon-Mobil and BP and serves on the organising committee of the biannual Engineering Foundation Conferences on heat exchanger fouling and cleaning. He has parallel activity on cleaning, primarily of food-based soils and has organised two international conferences on this topic. He has published over 30 Journal articles on fouling and cleaning of heat transfer systems and is the Food Fouling and Hygiene Subject Editor of *ICHEME Transactions C*.

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The Principal Investigator Mr. S.J.Pugh is head of the fluid dynamics, heat transfer and physical properties groups at IHS ESDU of London. This company was formed as the Technical Department of the Royal Aeronautical Society in 1940, and branched out from the aerospace industry in the 1970's with support from the principal engineering institutions in the UK and the DTI. It produces, under the guidance of expert, industrially-based committees, high-quality engineering data and software for industry and the Universities. IHS ESDU has been working on fouling since the mid-1980's, with particular emphasis in the last five years on crude oil