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TWO PHASE FLOW STUDIES IN THE UNITED KINGDOM

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1. INTRODUCTION

An international AGARD Round Table Discussion was held in Trondheim, Norway, on 23 September 1982 at which the various participating countries presented reviews of their national programmes on two-phase flow. This present review for the U.K. was prepared on the basis of a request for information sent to the various organisations in the U.K. doing work in this area. The response was very positive and a very large amount of information was supplied. Replies were received from the following centres (the names of the Correspondents being given in parenthesis):

University of Birmingham, Department of Mechanical Engineering (Dr. F. Bakhtar)
University of Bradford, Schools of Chemical Engineering (Prof. C. Hanson and Dr. W. H. Granville)
University of Bristol, Department of Mechanical Engineering (Dr. Y. R. Mayhew)
British Hydromechanics Research Association (BHRA Fluid Engineering) in collaboration with *Fluid Engineering Unit, Cranfield Institute of Technology (Dr. R. C. Baker)*
University of Cambridge, Department of Applied Mathematics and Theoretical Physics (Dr. N. Thomas)
University of Cambridge, Department of Chemical Engineering (Prof. J. F. Davidson)
University College, Cardiff, Department of Mechanical Engineering and Energy Studies (Dr. N. Syred and Dr. C. J. Bates)
Central Electricity Generating Board, Berkeley Nuclear Laboratory (Dr. S. J. Board)
Central Electricity Generating Board, Central Electricity Research Laboratories, Leatherhead (Dr. P. R. Farmer)
Central Electricity Generating Board, Marchwood Engineering Laboratories (Dr. B. Chojnowski)
City University, Department of Mechanical Engineering (Dr. D. H. Gothan)
Glasgow College of Technology (Dr. D. Chisholm)
Heriot-Watt University, Department of Mechanical Engineering (Dr. A. Dickson)
Imperial College of Science and Technology, London, Computational Fluid Dynamics Unit (Prof. D. B. Spalding)
Imperial College of Science and Technology, London, Department of Chemical Engineering and Chemical Technology (Dr. G. H. Anderson, Dr. M. Streat and Prof. F. J. Weinberg)
Imperial College of Science and Technology, Department of Mechanical Engineering (Prof. J. H. Whitelaw and Dr. R. I. Crane)
University of Leeds, Department of Mechanical Engineering (Dr. F. R. Mobbs)
University of Liverpool, Department of Mechanical Engineering (Dr. D. J. Ryley)
University College, London, Department of Chemical and Biochemical Engineering (Prof. P. N. Rowe)
University of Manchester, Simon Engineering Laboratories (Dr. M. J. Watts)
National Engineering Laboratory, Heat Business Centre (Dr. T. J. S. Brain)

National Engineering Laboratory, Hydrocarbon Flow Measurement Business Centre (Dr. W. C. Pursley)
University of Oxford, Department of Engineering Science (Dr. P. B. Whalley)
Queen Mary College, London, Department of Mechanical Engineering (Dr. J. W. Rose)
Queen Mary College, London, Department of Nuclear Engineering (Prof. D. C. Leslie)
University of Sheffield, Department of Chemical Engineering and Fuel Technology (Prof. J. Swithenbank)
University of Strathclyde, Glasgow, Department of Thermodynamics and Fluid Mechanics (Dr. D. H. Rooney)
University College of Swansea, Department of Chemical Engineering (Prof. J. F. Richardson)
United Kingdom Atomic Energy Authority, Harwell Laboratory, Engineering Sciences Division (Dr. G. F. Hewitt)
United Kingdom Atomic Energy Authority, Winfrith Laboratory, Safety and Engineering Science Division (Mr. G. L. Shires)
Warren Spring Laboratory, Materials Handling Division (Dr. P. L. Bransby)

Each submission was examined and summarised, and up to five illustrative papers listed. The summaries and illustrative references are given at the end of this paper. Two points should be stressed; firstly, the centres approached may not constitute the full list for the U.K. and, secondly, such was the amount of information submitted that it would be impossible to do justice to it in any paper of reasonable length. One hopes that at least a general indication of work in each centre is given in the Summaries and that people wishing to have further information will make contact with the appropriate correspondent.

In what follows, a few examples are given of work going on in the U.K.; these have been selected somewhat randomly with the object of illustrating the various fields.

2. PARTICLE SIZE MEASUREMENT

Interest in particle technology is ubiquitous throughout the United Kingdom. Work is proceeding in many centres, the particles being solid or liquid (droplets). Obviously, the measurement of particle size is critically important and there are a number of new developments being pursued. These include the development of sophisticated photographic techniques (e.g. at Imperial College, Ow & Crane 1980†), tomographic defraction techniques (University of Sheffield) and laser-Doppler based techniques (UKAEA Harwell in association with University College Cardiff). The principle of the tomographic technique is illustrated in figure 1. A beam of laser light passes through the droplet stream and is diffracted, the diffracted light passing through a Fourier transform lens and being deposited on a detector containing a series of annular rings. For a given beam, the dropsize distribution can be determined and by moving the beam through a succession of angles, the dropsize distribution may be determined as a function of radial position within the droplet stream by applying the principles of "tomography". Typical results for dropsize distribution obtained at several radial positions are illustrated in figure 2.

In the dropsizer developed jointly between University College, Cardiff and UKAEA Harwell, a two-colour principle is employed as illustrated in figure 3. Droplets passing through the LDA scattering volume emit scattered light at both frequencies. The signal is validated (indicating that the droplet is passing centrally through the scattering volume) only when pulses of both colours are seen. The droplet size is then a function of the pulse amplitude. The Farmer visibility method is used to self-calibrate the instrument for the lower range of droplet sizes. Since the freauency of the pulses is indicative of the velocity, then simultaneous dropsize and velocity data can be obtained as is illustrated in figure 4.

†The papers referred to are listed at the end of the summary for each centre.

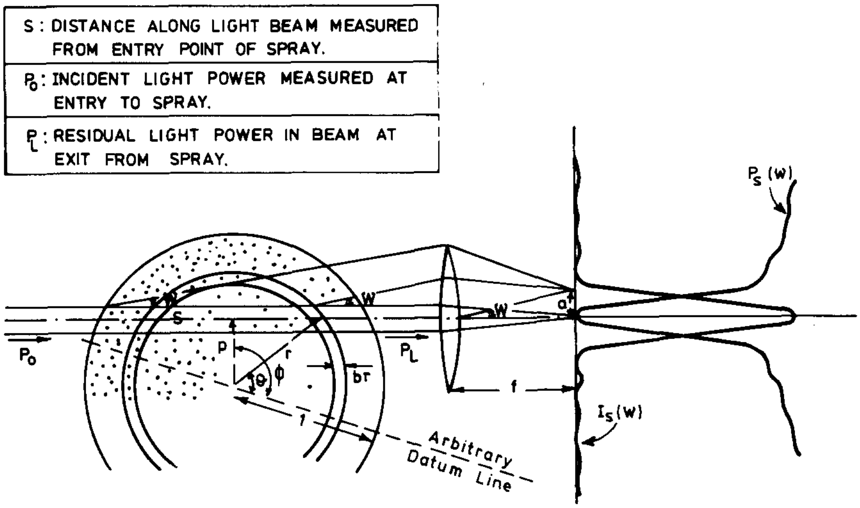

Figure 1. Principle of tomographic diffraction techniques for dropsize measurement (University of Sheffield, Yule *et al.* 1981).

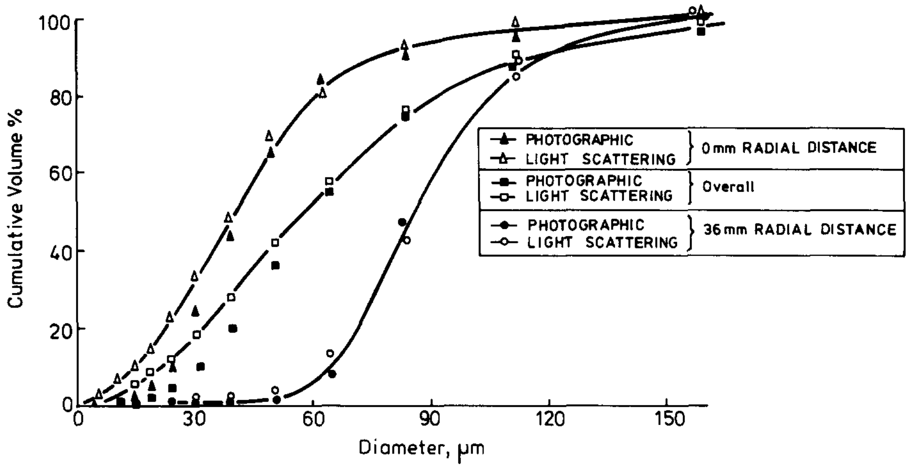

Figure 2. Dropsize data obtained by photographic and light scattering techniques at various radial positions within a spray. (University of Sheffield, Yule *et al.* 1981).

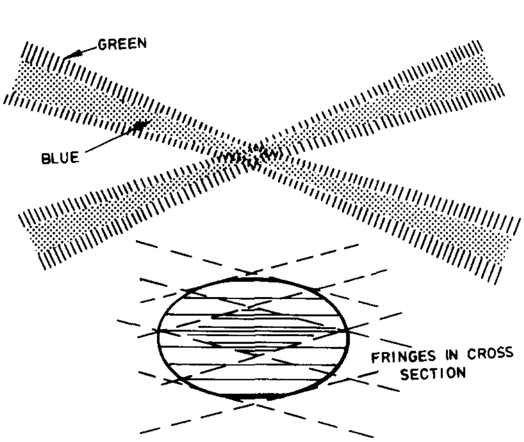

Figure 3. Dropsize measurement using a two-colour LDA system (University of Cardiff and UKAEA Harwell, Yeoman *et al.* 1982).

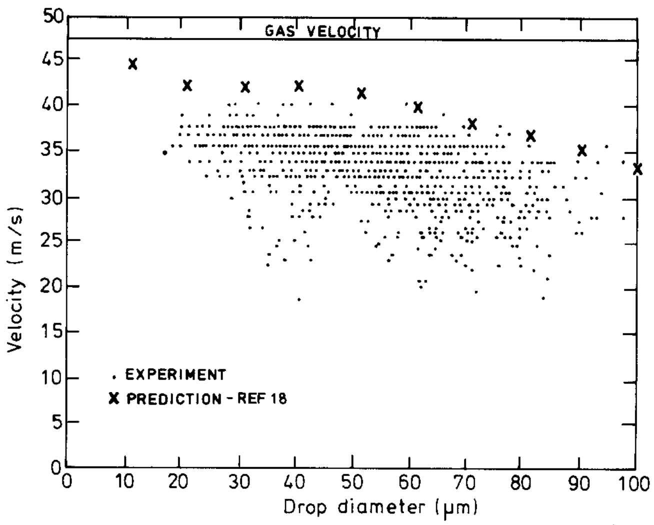

Figure 4. Simultaneous dropsize and drop velocity distribution in annular air-flow (University College Cardiff and UKAEA, Harwell–Yeoman *et al.* 1982).

3. PARTICLE TRACKING

A technique which seems to have met with widescale application in U.K. centres is that of *particle tracking*. Here, the motion and behaviour of particles or drops is simulated numerically. Two examples here are recent studies at Imperial College on the flow of gas through a converging-diverging nozzle and work at Oxford University/UKAEA Harwell on the motion of droplets in condensing and evaporating systems. The first of these examples is illustrated in figure 5. Note how the solid particles respond only slowly to changes in the gas velocity as the flow passes through the nozzle. The larger the particle density, the slower the response.

Figure 6 illustrates recent work carried out jointly between the University of Oxford and UKAEA Harwell on droplet behaviour in two cases, namely condensation of a superheated vapour and post-dryout heat transfer. The parameters calculated on a local basis include

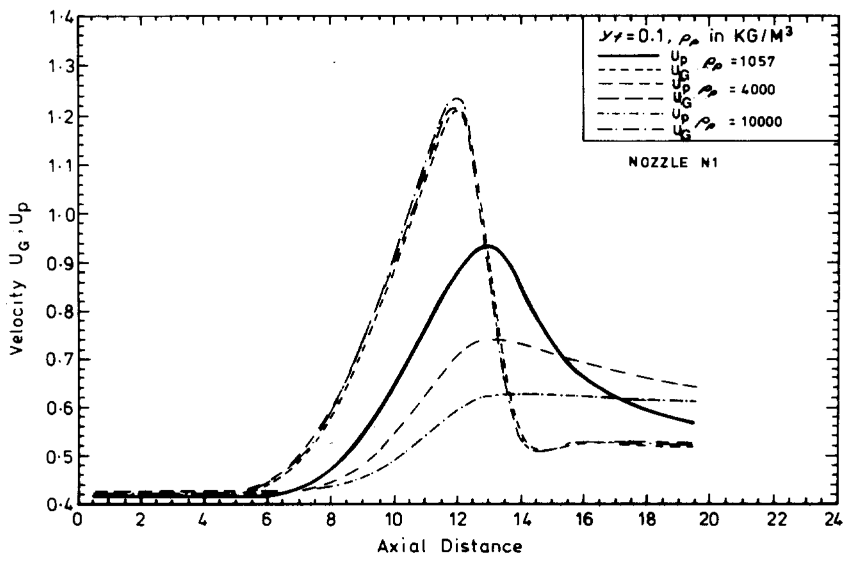

Figure 5. Variation of gas (u_G) and particle (u_p) velocities in a nozzle with a shock wave in the diverging section. Solid mass fraction = 0.1, particle diameter = 200 μm (Crane, Imperial College).

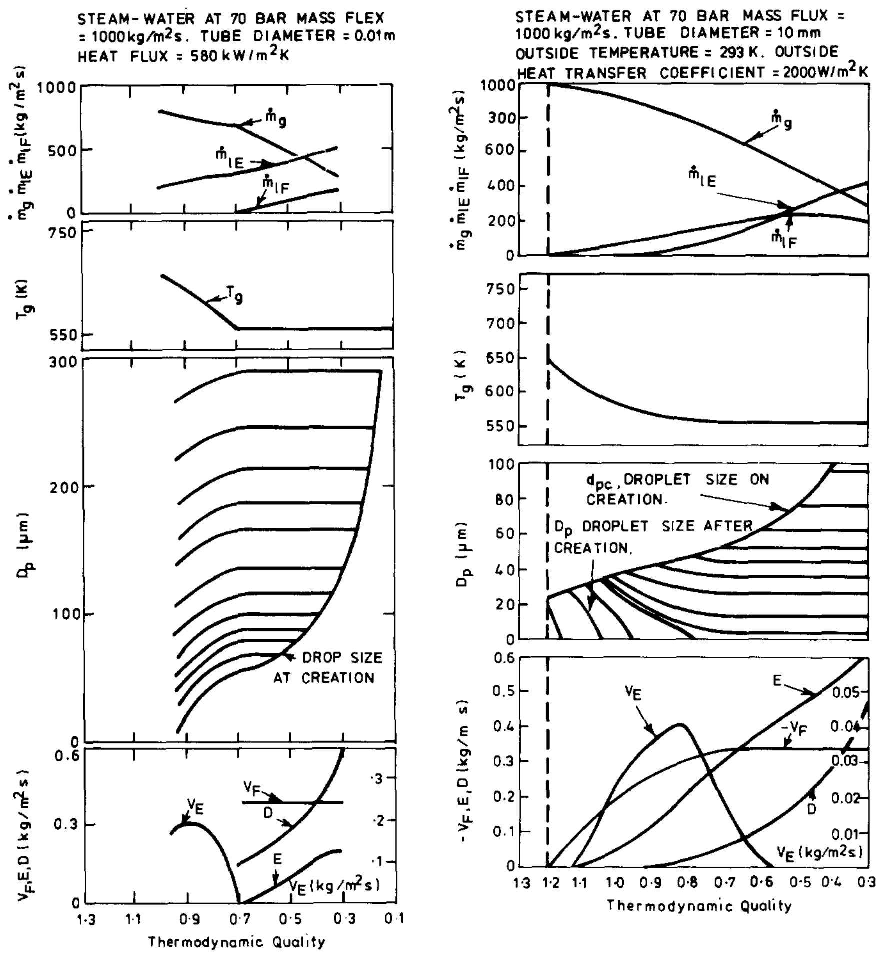

Figure 6. Calculations of local parameters in evaporating flows with dryout and a subsequent post-dryout region (left) and with condensation of a superheated vapour (right) (UKAEA Harwell/University of Oxford, Whalley *et al.* 1982).

dropsize D_p, rate of drop entrainment E, rate of drop deposition D, rate of film evaporation V_F, rate of droplet evaporation V_E, vapour temperature T_G vapour flow rate $\dot{m}_G$ film flow rate $\dot{m}_{LF}$ and entrained droplet flow rate $\dot{m}_{LE}$. Although many of these parameters cannot be measured, the overall predictions from such stepwise methods agree well with experimental measurements of parameters such as exit quality and channel wall temperature.

4. SLUG FLOW

In gas–liquid systems, perhaps the most important flow regime transition is that into slug flow and a number of centres are working in this area including CEGB, Leatherhead (Gardner 1979) and University of Cambridge, Department of Chemical Engineering (Davidson 1979). Figure 7 illustrates work carried out at Cambridge using a system designed to allow the observation of a stationary air—oil slug in a falling water stream. The photograph of the oil slug clearly indicates the complex recirculation patterns within the slug itself.

5. ANNULAR FLOW STUDIES

Annular flow is arguably the most important type of gas–liquid flow and has been the subject of a long term research programme at Harwell, which has been particularly concerned with vertical annular flows. Figure 8 exemplifies the recent Harwell work in this area and shows

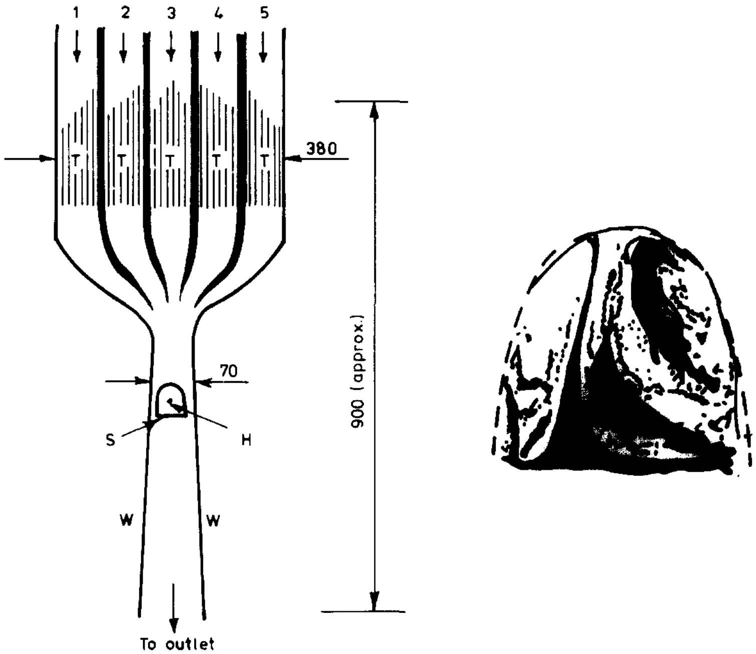

Figure 7. Apparatus for maintaining a stationary air or oil slug in a falling water stream. Photograph of oil slug showing internal circulation. (University of Cambridge, Department of Chemical Engineering, Davidson *et al.* 1979).

simultaneous measurements of wall shear stress and liquid film thickness at a given location in air–water annular flow in a vertical tube. Note the close correlation between the large disturbance waves on the interface and the existence of peaks in the wall shear stress.

Extensive studies have been made of horizontal annular flow at, for instance, CEGB Leatherhead, and figure 9 shows simultaneous film thickness measurements at the top and bottom of an air–water flow; note the large differences in both the wave structure and mean film

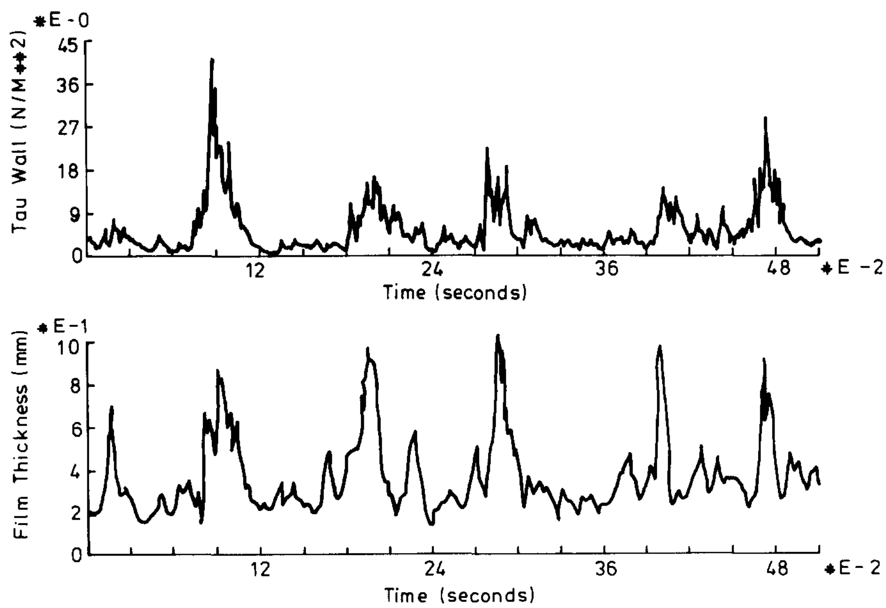

Figure 8. Simultaneous measurements of wall shear stress and liquid film thickness in air–water annular flow (UKAEA Harwell/University of Oxford–Martin and Whalley 1982).

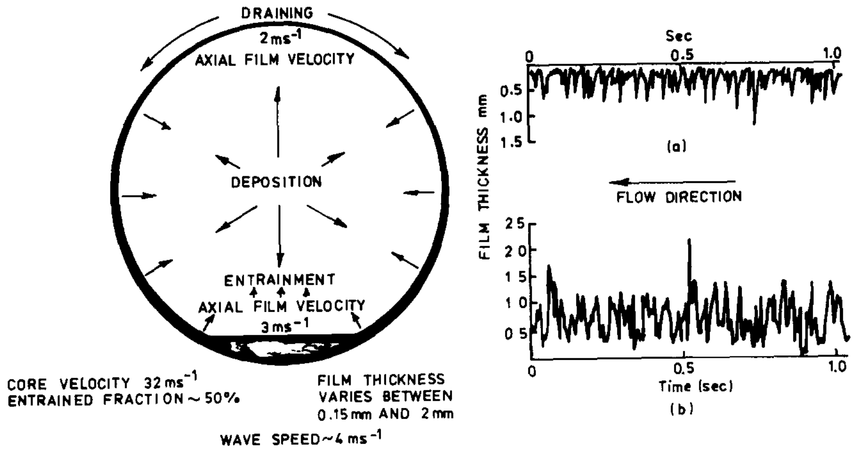

Figure 9. Film thickness measurement and droplet motion in horizontal annular flow (CEGB, Leatherhead–Fisher and Pearce 1978).

thickness between the bottom and top of the tube in horizontal flows. The large waves produce droplets and these droplets are deposited around the surface of the tube, the deposited droplets forming a film which drains down towards the bottom.

6. PIPE LINE FLOWS

Obviously, pipe-lines have great economic importance in the context of fluid transportation, including various two phase fluids. This is reflected in the large range of projects being carried out in the U.K. on pipe-line flows. In the gas–liquid flow area, the National Engineering Laboratory has been making measurements of pressure drop, void fraction, etc. in pipe lines and is currently constructing a new apparatus for these studies. UKAEA Harwell is embarking on a multi-client project for modelling and instrumentation of pipe-line flows and the University of Swansea is particularly involved in studies of drag reduction by air injection in the case of non-Newtonian flows. An example of this drag reduction is illustrated in figure 10. Similar results have been obtained at the Warren Spring Laboratory.

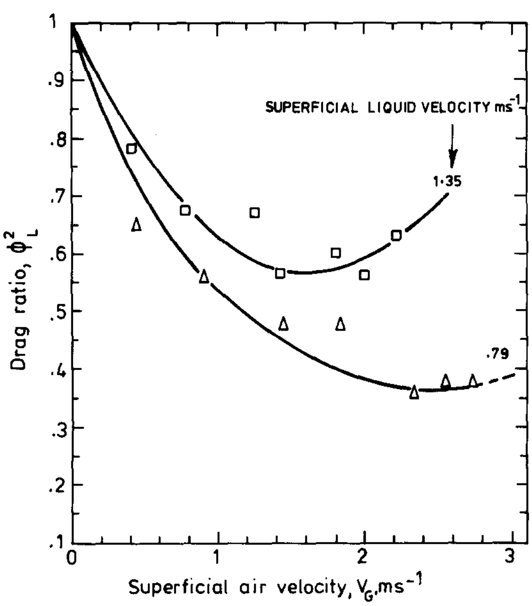

Figure 10. Effect of air flow on pressure gradient in the flow of acqueous kaolin (24.4% by volume) suspensions. University College Swansea.

Liquid–solid flows have been studied at University College, Swansea (where the main interest is in their non-Newtonian behaviour), at BHRA Cranfield (in the context of hydraulic conveying) and at the Warren Spring Laboratories (where the emphasis has been on systems with very high solids concentration). Gas–solid flows have been studied at Queen Mary College, at UKAEA Harwell (in the context of the work for the Separation Process Service, SPS, on dryers) and at Warren Spring Laboratory (where the emphasis has been pneumatic conveying).

7. FLOW MEASUREMENT

Flow measurement in two-phase systems has been a subject of considerable attention and importance. Flow measurement of gas–liquid flows is being studied at the National Engineering Laboratory and at Strathclyde University. Gas–solid flows are being investigated at BHRA Cranfield and at the Warren Spring Laboratory; these two centres are also involved in liquid/solid flow metering. Work on liquid–liquid (oil–water) systems is proceeding at the National Engineering Laboratory (NEL); here, there is an obvious interest in the extent to which water (e.g. sea water) becomes entrained in oil pipe line flows. NEL have built a special rig to investigate the accuracy and means of sampling of such flows, the sampling methods being illustrated in figure 11.

8. FLUIDIZED BEDS

The UK has a number of long term programmes on fluidization. These include the following:

(1) *University College, London.* A whole range of studies is taking place, with more emphasis recently on high pressure fluidized bed systems. A variety of experimental techniques have been developed, in particular the use of X-ray photography, to observe bubble motion in fluidized beds. Other studies include those on chemical reactions, flocculation etc.

(2) *University of Cambridge, Department of Chemical Engineering.* Recent studies in this Department include heat transfer to tubes immersed in fluidized beds and studies of the elutriation of particles from beds. This latter problem is very important since the particulate content of off-gases from fluidized beds can be particularly troublesome in downstream equipment.

(3) *University of Sheffield.* Here, the main emphasis has been on fluidized bed combustion both of normal fuels and also of various waste products.

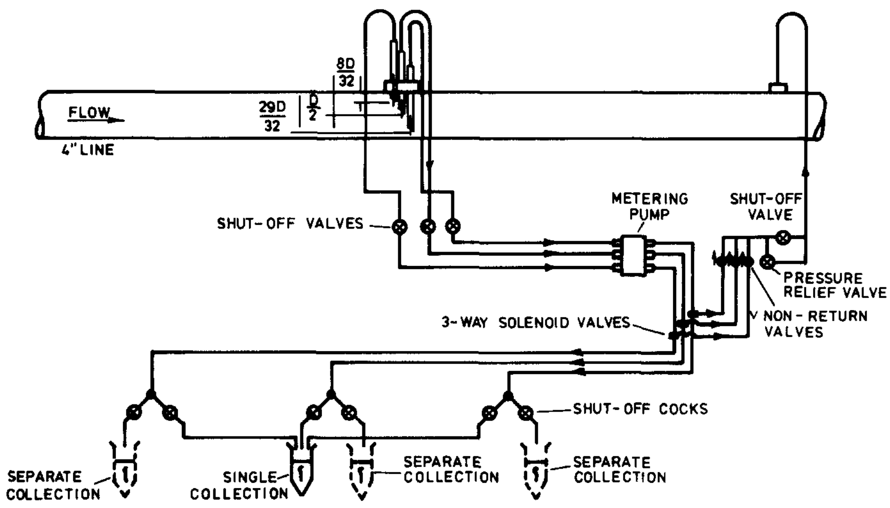

Figure 11. Flow metering of liquid–liquid flows; development of sampling techniques for measurement of water content of oil–water flows. National Engineering Laboratory.

A programme on fluidization has also been started by HTFS at Harwell and the National Coal Board is heavily involved in the commercial exploitation of fluidized bed combustion systems (this latter work is not summarised in this present document).

9. EQUIPMENT STUDIES

It is very striking that much of the work on two phase systems is gradually changing emphasis to be much more directly applicable to various types of equipment. This reflects changes in funding sources and is certainly not an indication that the essential basic research in two phase flow systems has been done! Amongst the equipment types being studied are the following:

(1) *Turbines.* Work associated with droplet formation and behaviour in wet steam turbines is proceeding at the University of Birmingham, Imperial College and the University of Liverpool. As an illustration of this work, figure 12 shows pressure and Mach number profiles calculated numerically for flow over a turbine blade for a condensing steam system.

(2) *Mass transfer equipment.* Here, a number of centres are involved in the study of two phase flow problems in distillation systems. The University of Bradford has an extensive programme on liquid–liquid systems (mixer settlers, pulsed columns, etc.).

(3) *Condensers.* Condensers are important not only in the power industry, but also in the process of industry. This has led to an extensive programme on condensers and condensation at the Heat Transfer and Fluid Flow Service (HTFS) centres at Harwell and NEL. Work is also proceeding in the Department of Mechanical Engineering at Queen Mary College and at the University of Manchester (this latter work is in the Department of Chemical Engineering at UMIST—no summary is given of the work in this Department).

(4) *Filters.* Filtration systems are important for the separation of solid particles from both liquids and gases. The leading centre in this area in the United Kingdom is the Warren Spring Laboratory, whose work is incorporated into the Separations processes Service (SPS) which is operated in collaboration with Harwell.

(5) *Boilers.* Here, the main research emphasis has been on power generation boilers and work closely simulating actual boilers is being carried out at CEGB, Marchwood. Model studies related to this work are being pursued at CEGB, Leatherhead. The CEGB Laboratories have very large scale facilities for testing full-scale boiler tubes under realistic conditions.

(6) *Kettle reboilers.* Kettle reboilers are used extensively in providing a vapour flux for distillation columns. They have commonly been considered to be essentially pool boiling

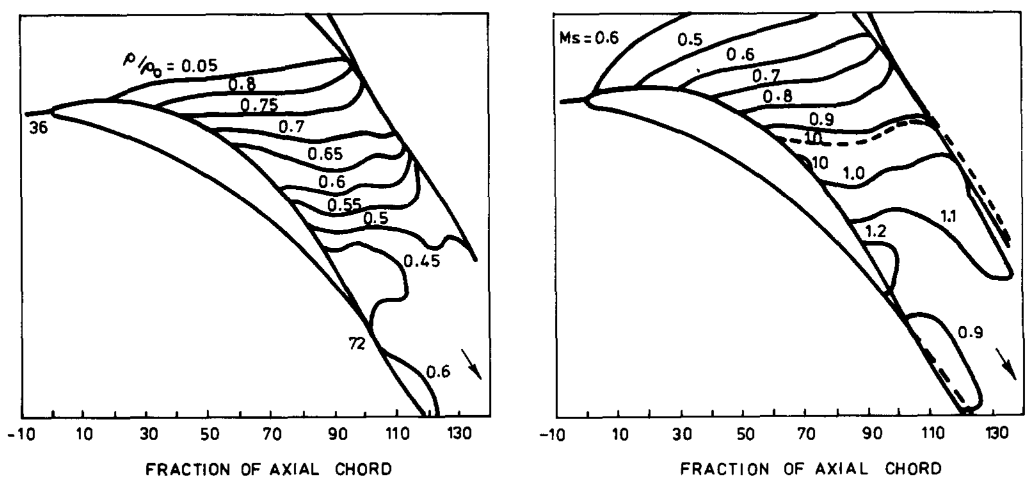

Figure 12. Pressure ratio and Mach number predictions for flow of condensing steam over a turbine blade (Bakhtar, University of Birmingham).

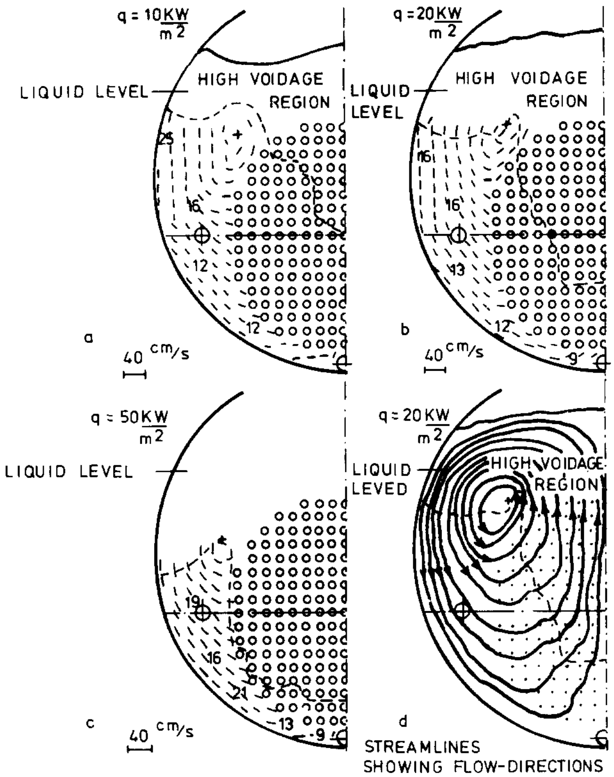

Figure 13. Circulation patterns in a kettle reboiler (Heriot Watt University, Schuller and Cornwell 1982).

systems, though recent studies carried out on behalf of HTFS (Harwell/NEL) at Heriot Watt University have revealed that the kettle reboiler is essentially a circulating system as illustrated in figure 13.

(7) *Nuclear reactor safety.* Work in the nuclear area has been an obvious source of funding on two phase flow systems and there is renewed emphasis in this area following the U.K. Government's decision to investigate the possibility of embarking on a programme of construction of Pressurized Water Reactors in the U.K. The main centres for this work are the UKAEA Laboratories at Winfrith and Harwell and the CEGBs Laboratories at Leatherhead and Berkeley. However, University centres such as Queen Mary College and Strathclyde University are becoming increasingly involved. The work covers not only the traditional reactor problems of void fraction, critical heat flux, critical flow, etc. but also a new range of problems arising from the consideration of loss-of-coolant accidents (LOCAs) beyond the previously accepted design base. In such accidents, the fuel may be severely damaged, may form debris beds, may melt and lead to fuel-coolant interations (FCIs) giving vapour explosion. An example of the work being carried out in this latter area is on the determination of the maximum heat removal from debris beds as shown in figure 14. If the heat can be removed, this would prevent further melting and degradation of the fuel and it is obviously important to fully understand the limits.

(8) *Geothermal wells.* Studies relating to steam supply from geothermal wells are pursued at the University of Liverpool. Methods have been developed to predict the pressure, quality and void fraction profiles in wells and these have been compared with measured data. An example of the results of such calculations is shown in figure 15.

(9) *Crystallizers.* Crystallization studies are being pursued at University College, London

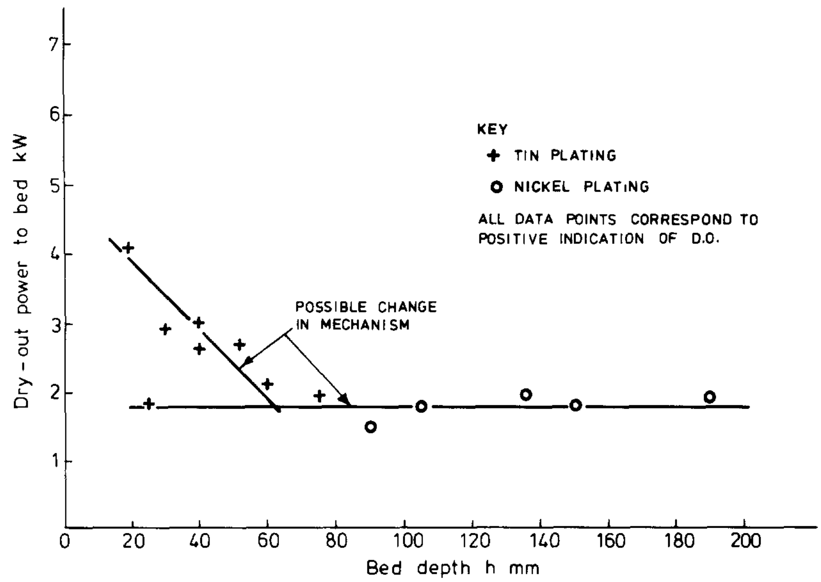

Figure 14. Power to dryout in a bed of 2-mm particles immersed in a pool of demineralized water (UKAEA Winfrith–Shires & Stevens 1980).

and (as part of the SPS Service) at UKAEA Harwell. This is an area where there remain formidable mass, heat and flow problems to be resolved.

(10) *Combustion systems.* This is an area which is being actively pursued as part of the HTFS service at both Harwell and NEL. Other main centres are Imperial College, London and the University of Sheffield. One of the main emphases in the combustion area over the past decade has been the increasing application of optical diagnostic techniques. LDA methods are being applied at Harwell, Sheffield, Imperial College and a number of other centres. Laser Raman methods are being developed and applied, particularly, at Harwell. An example of the usefulness of such optical methods is shown in figure 16 (from the University of Sheffield) where contours of liquid volume concentration have been measured in an evaporating spray jet at two temperature levels.

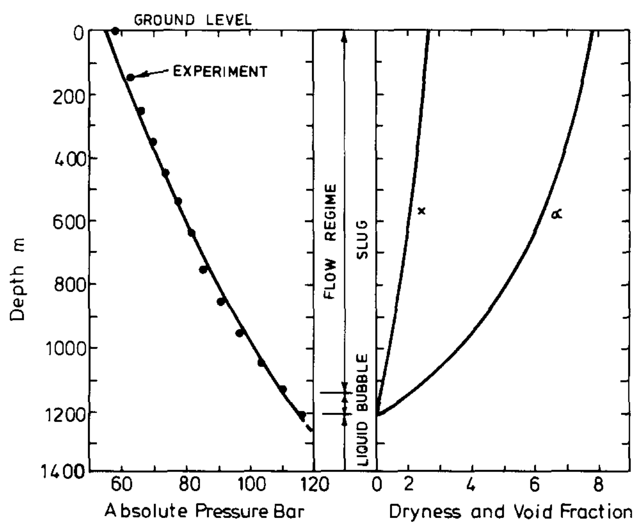

Figure 15. Pressure, quality (dryness) and void fraction predictions in a geothermal well with base pressure 196.9 bar, 2293 m deep and with a bore diameter of 0.1 m (lower part) and 0.16 m (upper part) University of Liverpool–Ryley & Parker 1982).

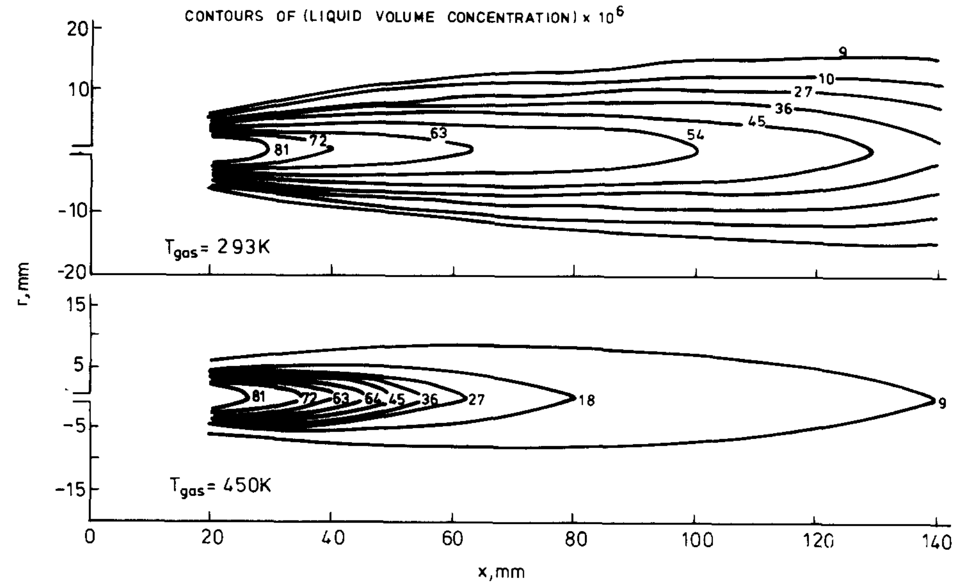

Figure 16. Liquid volume concentration profiles in evaporating spray jets measured by laser tomography (University of Sheffield–Yule *et al.* 1982).

(11) *Separators.* Vapour–liquid separation is of great importance both in power generation systems and in pipe line systems. Work in the former area has been pursued over many years at, for instance, CEGB Leatherhead and is leading to improved separator design and performance.

Obviously, it has been possible to highlight only a few aspects of the many equipment studies being carried out in the U.K. Further details are given in the Summaries.

10. NUMERICAL PREDICTION METHODS

With the increasing complexity of systems, with the increasing cost of experimental studies and with the decreasing cost of computation, emphasis is gradually switching towards numerical prediction methods for two phase flow systems. Perhaps the best known centre for this kind of work in the U.K. is the Computational Fluid Dynamics Unit at Imperial College, which works in close association with CHAM Ltd., a private company which exploits computer prediction methods for various commercial applications. Numerical prediction methods for, for instance, furnaces are being developed at HTFS Harwell and at the University of Sheffield.

Extensive developments have been made at, for instance, CEGB Marchwood on the preparation of simulation models for large boiler systems. The CEGB model (NUMEL) can be applied to the steady-state, to linear stability analysis and, more recently, to transient behaviour. Work on numerical modelling of more fundamental aspects of two phase flow is proceeding at the University of Cambridge, Applied Mathematics and Theoretical Physics Department. Here, for instance, models are being developed for bubble motion and entrainment by large scale vortices.

11. CONCLUSION

This survey of U.K. work on two phase flows has revealed the very considerable breadth and depth of the studies proceeding. Although it is clearly impossible to do justice to all of the work within the scope of this present exercise, it is hoped that workers at the various centres will find the information contained herein (and in particular in the Summaries) useful in making contact with other workers in similar and related fields.

SUMMARIES OF WORK BEING CARRIED OUT AT VARIOUS UNITED KINGDOM CENTRES

University of Birmingham, Department of Mechanical Engineering, South West Campus, The University of Birmingham, P.O. Box 363, Birmingham B15 2TT.
Correspondent: *Dr. F. Bakhtar.*

Multiphase flow work in this department has concentrated on the problems of *wet steam flow in turbines.* During its expansion through a turbine, steam crosses the vapour/liquid phase boundary and the subsequent turbine stages have to operate on a two-phase fluid. A special characteristic of wet steam is that the liquid phase consists of a large number of very small sub-micron droplets which are carried by the vapour. These droplets cause losses of output which are collectively known as wetness losses. In the studies at Birmingham, computer programs have been developed which predict the one-dimensionless flows of nucleating and wet steam with reasonable accuracy over a range of pressure. These high-lighted the potential existence of many problems which cannot be predicted by the traditional methods. For instance, it was shown that the heat release resulting from phase change can upset the radial equilibrium of the flow in a turbine stage. More recently, the equations describing transonic two-phase blade-to-blade flows of steam have been examined and found to be capable of solution by the time marching method. Large variations in flow properties where discovered, particularly downstream of the trailing edge. The solutions also showed a reduction of 5° in the flow deflection for the nucleating flow compared with one in which the fluid remained dry throughout.

Illustrative papers

BAKHTAR, F. & YOUNG, J. B. 1978 A study of choking conditions in the flow of wet steam. *Proc. Inst. Mech. Engng* **192**, 237–242.

BAKHTAR, F. & GHASSEMI, B. 1979 A study of nucleating and wet steam flows in a high pressure turbine. *Conf. Steam Turbines for the* 1980'*s*, *London*, October 1979, *Inst. Mech. Engrs Conf. Publications* 1979–12, SSBN 0-85298-440-5, Paper C191/79, pp. 327–336.

BAKHTAR, F. & MOHAMMADI-TOCHAI, M. T. 1980 An investigation of two-dimensional flows of nucleating and wet steam by the time marching method. *Int. J. Heat & Fluid Flow* **2**, 5–18.

University of Bradford, Schools of Chemical Engineering, Bradford, West Yorkshire, BD7 1DP.
Correspondents: *Prof. C. Hanson and Dr. W. H. Granville.*

The main thrust of the work in this department is concerned with *liquid–liquid systems* with particular reference to *mass transfer and reaction systems.* Currently, the performance of four different extraction columns is being studied with the aim of obtaining a better understanding of the effect of system properties on performance and to confirm (or otherwise) the present standard design procedures. It is hoped to obtain some guide on how one can best use the most appropriate column for a system of given physical properties.

An experimental and theoretical study is also under way on liquid–liquid mixing with the object of improving the design and performance of *mixer-settlers.* This is sponsored by the Minerals Industry Research Organisation (MIRO) and is aimed at the prediction of the necessary power consumption, pumping capacity, hold-up characteristics, phase inversion, minimum conditions for dispersion and dropsize characteristics. There is an incomplete understanding in this area with regard to industrial applications and the aim of the work is to improve design methods. Some work is also going on on *static mixers* for liquid–liquid systems.

Work has also been done on *vapour–liquid flows* with experimental measurements being made of adiabatic flow of liquid and gaseous nitrogen. A new relationship was developed between pressure drop and void fraction which fitted this data, and the data for other substances, with an rms error of the order of 15–30%.

Illustrative papers

GODFREY, J. C. & GRILC, V. 1977 Dropsize and dropsize distribution for liquid–liquid dispersion in agitated tanks of square cross section. *2nd European Conf. Mixing, Cambridge England*, Paper C120 pp.

GODFREY, J. C. & SLATER, M. J. 1978 Co-current flow systems for liquid extraction. *Chem. Ind.* **19**, 745.

GODFREY, J. C. & GRILC, V. 1979 Hold-up characteristics in continuous liquid–liquid mixers. *Proc. 3rd European Conf. Mixing, York, England.*

WHYATT, N. 1978 Adiabatic two-phase flow of liquid and gaseous nitrogen. Ph.D. thesis, University of Bradford.

University of Bristol, Department of Mechanical Engineering, Queens Building, University Walk, Bristol, B58 1TR.

Correspondent: Dr. Y. R. Mayhew.

This department has had a long-term programme of work on condensation heat transfer in a variety of geometries, including vertical surfaces, tubes and cylinders in cross flow. In recent years, much of the research effort has been devoted to the simulation of certain aspects of condensation by using sintered-bronze tubes with suction, involving the flow of air, the suction simulating the vapour motion during the condensation process. In some recent tests, for instance, flow over in-line square and triangular tube banks was studied and the results show that suction causes a net reduction of pressure loss, after allowing for the effect of extraction of momentum of the flowing air. The reduction depends on the array configuration, but in all cases it is less than might be expected from delays in separation observed with single tubes. Other condensation studies carried out by the department include those on inundation effects, condensation on fluted tubes, pressure losses in headers in multi-pass heat exchangers and dropwise condensation.

Illustrative papers

AGGARWALL, J. K. & HOLLINGSWARTH, M. A. 1973 Heat transfer for turbulent flow with suction in a porous tube. *Int. J. Heat Mass Transfer* **16**, 591–609.

LEE, N. K., HOLLINGSWORTH, M. A. & MAYHEW, Y. R. 1982 *Proc. 7th Int. Heat Transfer Conf., Munich*, (Edited by U. GRIGULL *et al.*), Hemisphere Pub. Corp., ISBN 0-89116-342-5, **5**, Paper CS18, pp. 107–112.

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NOBBS, D. W. & MAYHEW, Y. R. 1976 Effect of downward vapour velocity and inundation on condensation rates in horizontal tube banks. NEL Rep. No. C19, pp. 39–52.

British Hydromechanics Research Association (BHRA Fluid Engineering) in collaboration with **Fluid Engineering Unit, Cranfield Institute of Technology**, Cranfield, Bedford MK43 OAJ.

Correspondent: Dr. R. C. Baker.

BHRA/Cranfield are engaged in a wide range of research in *solid–liquid*, *solid–gas* and *gas–liquid* flows. The solid–liquid flow work is concerned with flow in pipe lines, rotating machines and pumps with the emphasis on flow metering, pipe line component losses and wear prediction.

In the work on *solid–gas* flow, the main aim has been related to *pneumatic conveying* and with the prediction of pressure losses in both dense and lean phase conveying. Work has been proceeding towards a mathematical representation of particle flows in pneumatic transport.

In the work on *gas–liquid* systems, work has been proceeding on component pressure losses and on instrumentation development. Here, particular stress has been laid on the performance of commercial flow meters.

Illustrative papers

BAKER, R. C. & HEMP, J. 1981 Slurry concentration meters. *BHRA Fluid Engng Series* **8**.

BAKER, P. J. & JACOBS, B. E. A. 1979 A guide to slurry pipe line systems. Publ. by *BHRA Fluid Engineering*.

BAKER, P. J. 1982 Pneumatic conveying activities. Publ. by *BHRA Fluid Engineering Report*, No. RR1871, July 1982.

BAKER, R. C. & DEACON, J. E. 1983 Two phase flow measurement using commercial flow meters. To be presented at *BHRA Int. Conf. the Physical Modelling of Multiphase Flow, Coventry, England*, 19–21 *April* 1983.

FAIRHURST, P. 1982 Component pressure drop and straight pipe frequency analysis in two phase flow. M.Sc. Thesis, Cranfield Institute of Technology, 1982.

University of Cambridge, Department of Applied Mathematics and Theoretical Physics, Silver Street, Cambridge CB3 9EW.

Correspondent: *Dr. N. Thomas.*

This department is extensively involved in theoretical fluid mechanics and much of this work is relevant to, or concerned with, multiphase flow. Work is proceeding on *bubble motion in fluids*, including the generation of bubbles by plunging jets. A variety of turbulence models are being studied in the department, including models for rapidly distorted turbulent flows. Such models may have application for instance, in studying the inter-phase interactions in gas flow over a wavy liquid surface.

More recently, the Department has been involved in pipe line flow studies, including *liquid–liquid* (oil–water) flows.

Illustrative papers

AUTON, I. R. 1982 The motion of bubbles, drops and particles in fluids. Ph.D Thesis, University of Cambridge.

BRITTER, R. E., HUNT, J. C. R. & RICHARDS, K. J. 1981 Air flow over a two-dimensional hill: Studies of velocity speed-up, roughness effects and turbulence. *Q. J. Roy. Meteorological Soc.* **107**, 91–110.

GOLDRING, B. T., MAWER, W. T. & THOMAS, N. H. 1980 Level surges in the circulating water downshaft of large generating stations. *3rd Int. Pressure Surges Conf.* (*BHRA*), Canterbury, England.

THOMAS, N. H. 1982 Air demand distortion in hydraulic models: Experimental evidence of bimodal structure in air entraining flows and a scaling analysis of de-entrainment with special application to syphon priming. *Int. Conf. Hydraulic Modelling of Civil Engineering Structures* (*BHRA*), *Coventry, England.*

THOMAS, N. H., AUTON, T. R., SENE, K. & HUNT, J. C. R. 1983 Experimental and theoretical modelling of bubble transport and entrainment by large scale transient vortices in multiphase flows. *Int. Conference on the Physical Modelling of Multiphase Flow* (*BHRA*), Coventry, England.

University of Cambridge, Department of Chemical Engineering, Pembroke Street, Cambridge.

Correspondent: *Prof. J. F. Davidson.*

This department is a major centre in the U.K. for work on fluidized beds for coal combustion and gasification including the effects of transient behaviour, the effect of temperature gradients and the effect of pressures up to 20 bar. A major apparatus for the study of fluidized beds has been built at the Rutherford Laboratory, Harwell in which Cambridge (and other universities) are carrying out large scale studies. These include elutriation of fine particles from fluidized beds, heat transfer to vertical tubes in fluidized beds and heat transfer properties of non-bubbling gas fluidized beds. The department is also studying dense phase pneumatic conveying of particles through orifices.

The Department has been involved in *gas–liquid* flows for many years, and in particular on bubble flows. This latter work includes gas–liquid bubble columns, the stability of liquid circulation in bubble systems, the effect of liquid turbulence on bubble size and gas–liquid mass transfer and liquid mixing. Recent studies in this area include measurements of axial dispersion in bubble columns, bubble splitting in shear flow and studies on stationary bubbles in a downward liquid flow.

Illustrative papers

DAVIDSON, P. J., CROOKS, S. P., DAVIDSON, J. F. & HARRISON, D. 1979 Holding a two-dimensional bubble fixed by downward flow. *Chem. Engng Sci.* **34**, 1170–1172.

DAVIDSON, J. F. 1980 Research on fluidization in the department of Chemical Engineering, Cambridge. In "*Bulk Solids Handling*", *Trans.-Tech. Publications.*

KONRAD, K., HARRISON, D., NEDDERMAN, R. M. & DAVIDSON, J. F. 1980 Prediction of the pressure drop for horizontal dense phase pneumatic conveying of particles. *Pneumotransport* **5**, published by *BHRA Cranfield, Bedford, England.*

LEWIS, D. A. & DAVIDSON, J. F. 1982 Bubble splitting in shear flow. *Trans. Inst. Chem. Engng.* To be published.

LEWIS, D. A., FIELD, R. W., XAVIER, A. M. & EDWARDS, D. E. 1982 Heat transfer in bubble columns. *Trans. Chem. Engng* **60**, 40–47.

University College, Cardiff, Department of Mechanical Engineering and Energy Studies, Newport Road, Cardiff CF2 1TA.

Correspondents: *Dr. N. Syred and Dr. C. J. Bates.*

Work in this department is under way on both *gas cleaning* and on *dropsize measurement* in gas–liquid flow. The gas cleaning work has involved the development of a new design of cyclone dust separator and the study of fluidic regenerative circuits for filter cleansing; the work is supported by the Science and Engineering Research Council (SERC) and by the National Coal Board. In the new cyclone dust separator, a system of vortex collector pockets are added to the outer vortex chamber of the cyclone and these form a first stage dust collection system removing between 50 and 90% of the dust, depending on the particle size. The total pressure loss of the system is slightly lower than that of a conventional cyclone dust separator, whilst dust collection efficiencies of up to 95% at 1 μm have been recorded. Filters are typically used as a second stage gas cleaning system after cyclones and the usual practice is to clean the filters by back flushing; operation of conventional valves under the high temperature conditions (typically 700°C and 13.5 bar) is often not successful. The Department has developed a fluidic system to allow flow switching between filters, this being achieved by a combination of a vortex amplifier and an ejector.

The Department has also been involved in carrying out development work on dropsize measurement under contract from UKAEA, Harwell. The dropsize measurement device is self-calibrated and will operate over a wide range of particle sizes. The system employs a pair of two-colour coincident beams to create a two-fringe LDA system. The scattered light signals are processed digitally which permits rigorous validation procedures to be employed. The technique is now being employed in the Harwell diesel engine and annular flow studies.

Illustrative papers

BATES, C. J. 1979 Software consideration for use with a transient recorder/mini computer LDA system. *6th Biennial Symp. Turbulence*, Missouri-Rolla.

OWEN, I., PERERA, P. & SYRED, N. 1982 The application of fluidic valves to filter regeneration at elevated temperatures and pressures. *Inst. Chem. Engng Jubilee Symp., London*, April 1982.

OWEN, I. & SYRED, N. 1982 Fluidic control valves diverting high temperature gas flows during filter regeneration. *Filtration and Separation*, July–August 1982.

YEOMAN, M. L., AZZOPARDI, B. J., WHITE, H. A., BATES, C. J. & ROBERTS, P. J. 1982 Optical development and application of a two colour LDA system for the simultaneous measurement of particle size and particle velocity. AERE-R10468.

Central Electricity Generating Board, Berkeley Nuclear Laboratory, CEGB Berkeley, Gloucester.

Correspondent: Dr. S. J. Board.

The two phase flow work at this laboratory is concerned mainly with the assessment of loss-of-coolant accidents (LOCA's) in water reactors, and in particular the Pressurized Water Reactor (PWR). The laboratory has a number of rigs including a *multiple cluster rig* and a *blowdown rig.* The multiple cluster rig is aimed in particular at the study of the heat transfer consequences of ductile ballooning of the fuel rod cladding during a LOCA. The rig consists of 44 heater rods which are held vertically in a square array and are subjected to a variety of controlled thermal-hydraulic test conditions. A transparent shroud allows photographic study of water droplet dynamics. It is found that the blockage shapes studied so far cause a local enhancement of heat transfer under single phase steam cooling conditions though the blockage does cause an increase in the time required to quench the fuel element during the refilling of the reactor with water after the LOCA.

The *blowdown rig* is intended to provide data for subcooled and saturated blowdown from pipes at pressures up to 30 bar and 10 cm dia. The results will be compared with a one-dimensional two-fluid model developed at the Laboratory and embodied in their computer code CRACKPOT.

The Laboratory is well known for its work on fuel-coolant interaction (FCI) and has developed a theoretical model for detonation propogation leading to vapour explosion. Another aspect of post-accident heat removal (PAHR) being studied by the Laboratory is that of the quenching of debris beds by bottom flooding. Studies are also proceeding on droplet hydrodynamics during channel reflooding, for example work on droplet breakup at spacer grids.

Illustrative papers

ARDRON, K. H. 1977 A one-dimensional two-fluid model for the critical flow of initially saturated or sub-cooled liquids in a pipe. CEGB Rep. No. RD/B/N3967.

ARDRON, K. H. & HALL, P. C. 1981 Droplet hydrodynamics and heat transfer in the dispersed flow regime in bottom flooding. CEGB Rep. No. RD/B/5007N81.

ARDRON, K. H. & FAIRBAIRN, S. A. 1982 A method of predicting the temperature response of ballooning fuel rod cladding for PWR LOCA conditions. CEGB Rep. No. TPRD/B/0043N82.

HALL, P. C. & HALL, C. M. 1981 Quenching of heated particulate beds by bottom flooding, preliminary results and analysis. CEGB Rep. No. RD/B/5154N81.

HALL, R. W. & BOARD, S. J. 1979 The propagation of large scale thermal explosions. *Int. J. Heat Mass Transfer* **22**, 1083–1093.

Central Electricity Generating Board, Central Electricity Research Laboratories Leatherhead, Kelvin Avenue, Leatherhead, Surrey KT22 7SE.

Correspondent: Dr. P. R. Farmer.

Two phase flow work started at CERL in the mid-1960s and has continued with varying emphasis since then; initially, the work was on the prediction of critical heat flux in boiler tubes, basic studies being done in support of the full-scale tests at Marchwood (see below). Later, the emphasis changed to the problems of corrosion and the problems of water reactor safety.

Basic studies have continued from the 1960s to the present day on the hydrodynamics of *gas–liquid two-phase flow*, with particular emphasis on intermittent flows in horizontal tubes. The intermittency of the flow leads to transient dry wall conditions and this has a dramatic effect on corrosion. A specific feature of the work at CERL has been the extensive use of a refrigerant-flow boiling facility which gives fluid density ratios similar to those obtained with water at high pressure.

In addition to the continuing programme on basic two-phase flow, there are projects on *vapour/liquid separation, PWR safety, fluid dynamics of corrosion* and *pressure loss characteristics of resistance.* The steam drum separator is one of the most difficult items of plant to analyse from the fluid dynamics point of view. In some cases, these separators perform badly, leading to inefficient operation. The work at CERL has been aimed at the production of a computer model for prediction of steam drum performance and on the investigation of means of improving performance of these units. Experimental work on cyclone separator performance, and the characteristics of bubble separation in the liquid pool is being obtained from a full size section of a steam drum mounted on the CERL refrigerant rig.

The main emphasis of the *PWR safety studies* is on reviewing the so-called "evaluation models" which are aimed at giving conservative calculations relating reactor plant behaviour subsequent to a loss-of-coolant accident (LOCA).

One of the most troublesome areas in operating both conventional and nuclear power plant is that of erosion–corrosion. Here, the role of the CERL team has been to obtain information on the mass transfer processes, particularly in bends and flow restrictions. It is now believed that low level dosing with oxygen will provide an effective inhibitor against single-phase erosion–corrosion attack on mild steel. Two-phase erosion–corrosion is a more serious problem since the oxygen is not effective under these conditions and the problem is being studied using an analogue rig with the tests sections made of Plaster of Paris through which is passed an air–calcium sulphate solution mixture.

Illustrative papers

CONEY, M. W. E. 1980 Reduced scale, semi-quantitative modelling of accident behaviour in water reactor primary circuits using refrigerant-12. *Symp. Nuclear Reactor Safety Heat Transfer, International Centre for Heat and Mass Transfer,* Dubrovnik, September.

COLLINGS, T. M. 1981 The production of hydraulic losses for boiler stabilization. Paper at *Steam Boiler Plant Technology,* Institution of Mechanical Engineers, 7 October 1981, Paper No. C135/82, pp. 37–41.

FISHER, S. A., HARRISON, G. S. & PEARCE, D. L. 1978 Instrumentation for localised measurements with fast response in liquid/vapour flows. *Winter Ann. Meeting,* ASME, San Francisco, 10–15 December 1978, 8 pp.

FISHER, S. A. & PEARCE, D. L. 1978 A theoretical model for describing horizontal annular flows. *Int. Seminar on Momentum Heat and Mass Transfer in Two Phase Energy and Chemical Systems,* Dubrovnik, Yugoslavia, September.

GARDNER, G. C. 1979 Onset of slugging in horizontal ducts. *Int. J. Multiphase Flow* **5**, 201–209.

Central Electricity Generating Board, Marchwood Engineering Laboratories, Marchwood, Southampton, Hampshire SO4 4ZB.

Correspondent: Dr. B. Chojnowski.

The work at Marchwood is centered on the problem of high pressure boilers—performance, operational constraints, long term structural integrity and safety. The object is to develop models for steady-state, stability and transient response and to validate the models against both experimental and plant data.

The computer modelling studies are centered around the code NUMEL which is in an advanced stage of development and has already found national acceptance for Advanced Gas cooled Reactor (AGR) studies. The code calculates the steady-state performance and may be used to predict transients in flow or power. It is linked to routines which carry out dynamic instability threshold and growth rate calculations using a linearized frequency response method. Further extensions of the code are being undertaken to represent the complete behaviour of boilers including dryout and reflooding, feed flow limit cycling following transgress of dynamic instability threshold, flow instability under transient conditions, etc. Other modelling codes include ones for temperature stratification caused by partial dryout (ZENO), critical heat flux margin assessment (combining the FURDEC code for distribution of heat flux on furnace walls and the CRHEAT code for critical heat flux limit prediction) and transient modelling of drum boilers (NUMEL-MDB). Work has also started recently on PWR total plant models using the RETRAN code, with particular emphasis on the representation of the steam generator.

The experimental studies at Marchwood are centered on the 12 MW Boiling Water Test Facility which comprises of two rigs, the Boiler Dynamics Rig (290 bar maximum pressure, 250 l./min. flow pump capacity) and the Boiling Water Rig 250 bar maximum pressure, 1000 l./min. flow capacity). Very extensive data on critical heat flux in large bore (32 mm and 52 mm) conventional boiler tubes have been generated using the Boiling Water Rig. This data covers both uniformly heated and side heated tubes, in vertical and inclined orientations. The data covers the pressure range 80 to 205 bars, the mass flux range 400–3300 kg/m^2s, heat fluxes in the range up to 1.3 MW/m^2 and qualities from −15% to +70%. The rig has also been employed for the measurement of voidage in serpentine geometry tubes under high pressure conditions, to investigate the effect of oil present in the water on critical heat flux limits and to obtain data in the post-dryout region (pressure range 140–180 bar, mass flux range 400–2250 kg/m^2s).

Illustrative papers

CHOJNOWSKI, B. & WILSON, P. W. 1974 Critical heat flux for large diameter steam generating tubes with circumferentially variable and uniform heating. *Proc. 5th Int. Heat Transfer Conf.*, Tokyo, Paper B6.5, 4, 260–264.

GREEN, C. H., LIGHTFOOT, P., DEAN, R. & CHOJNOWSKI, B. 1979 Feed flow limit cycling in AGR boilers. *BNES Conf. Boiler Dynamics and Control in Nuclear Power Stations*, 23–25 October, 1979, Bournemouth, England.

LIGHTFOOT, P., DEAN, R. T., GREEN, C. H. *et al.* 1979 NUMEL—a computer aid design suite for the assessment of steady-state, static-dynamic stability and transient responses of one-through steam generators. *BNES Conf. on Boiler Dynamics and Control in Nuclear Power Stations*, 23–25 October 1979, Bournemouth, England.

SCRUTON, B. & CHOJNOWSKI, B. 1980 The assessment of critical heat flux margins for furnace-wall tubes. *DGB Conf.: Forschung in der Kraftwerkstichnik.*

SCRUTON, B. & CHOJNOWSKI, B. 1982 Post-dryout heat transfer for steam-water flowing in vertical tubes at high pressure. *Proc. 7th Int. Heat Transfer Conf.*, Munich, September.

City University, Department of Mechanical Engineering, Northampton Square, London EC1V 0HV.

Correspondent: Dr. D. H. Gothan.

This department is involved in a variety of studies involving heat transfer in *gas–liquid* systems. In a recent project, measurements were made of the extent of droplet entrainment in condensing annular flows. Such entrainment is important in determining the hydrodynamic, and hence heat transfer, behaviour of the system. Another study concerned the heat transfer during bubble formation, this work being funded by the Admiralty in the context of new propulsion devices.

In collaboration with Oxford and Herriot–Watt universities, the department is involved in a project on waste heat recovery from diesel engines. This involves the use of organic cycles with consequent problems in the evaporation and condensation of the working fluids.

Illustrative papers

GOTHAN, D. H. T. 1982 Entrainment in condensing annular flow. To be published in *Int. J. Multiphase Flow.*

GOTHAN, D. H. T. & HAYNES, J. 1982 Heat transfer during bubble formation. *Int. J. Heat & Fluid Flow* **3**.

Glasgow College of Technology, Cowcaddens Road, Glasgow G4 OBA.
Correspondent: Dr. D. Chisholm.

Currently, three new rigs are under construction, namely a 0.3 m × 0.3 m two phase tunnel, a two phase pipe-line rig (diameters up to 15 cm) and an air-lift pump rig. The two phase tunnel will be used to obtain data on flow over tube banks and through packed beds. The onset of entrainment and associated pressure drop will be studied in the first instance. With the two phase pipe line, data will be obtained for horizontal pipes and for pipes with change of inclination to the horizontal. Entrainment, pressure drop and slug formation will be studied. With the air-lift pump rig, data will be obtained using viscous fluids in addition to water. At a later stage, *three-phase (air–oil water) systems will be studied.*

Illustrative papers

CHISHOLM, D. 1981 Flow of compressible two-phase mixtures through sharp-edge orifices. *J. Mech. Engng Sci.* **23**, 45–48.

CHISHOLM, D. 1981 Mass velocities under choked flow conditions in two-phase flashing pipe flow. *J. Mech. Engng Sci.* **23**, 309–311.

CHISHOLM, D. 1982 Prediction of the performance of air-lift pumps. To be published in *Int. J. Heat Fluid Flow.*

Heriot-Watt University, Department of Mechanical Engineering. James Nasmyth Building, Riccarton, Edinburgh EH14 4AS.
Correspondent: Dr. A. Dickson.

The department is carrying out studies (sponsored by HTFS) of boiling outside a tube bundle in a geometry simulating that of a *kettle reboiler.* By constructing a "slice" of the reboiler with a glass front, it has been possible to clearly visualize the flow and boiling behaviour. Clearly, the situation is dominated by the rapid circulation induced by boiling within the bundle, with water circulating down around it. This has led to the development of a theoretical (potential flow) model for circulation. Studies are also proceeding on other aspects of boiling, including boiling incipience due to contact angle hysteresis.

The Department has had a long term programme on *demisters* and difficulties in making reliable measurements of the spray has stimulated interest in sampling when conditions are not isokinetic. A simple instrument has been devised for these circumstances which is an improvement on the conventional cascade impactor.

Other studies in the department include the attenuation of *pressure waves* in bubbly mixtures and boiling and condensation of *immiscible mixtures* of organic fluids and water.

Illustrative papers

ADDLESEE, A. J. 1980 Anisokinetic sampling of aerosols at a slot intake. *J. Aerosol Sci.* **11**, 483–493.

CORNWELL, K. & SCHULLER, R. B. 1982 A study of boiling outside a tube bundle using high speed photography. *Int. J. Heat Mass Transfer* **25**, 683–690.

CORNWELL, K. 1982 On boiling incipience due to contact angle hysteresis. *Int. J. Heat Mass Transfer* **25**, 205–211.

SCHULLER, R. B. & CORNWELL, K. 1982. A theoretical model for recirculating flow in a boiler. *Chem. Engng Commun.* **13**, 271–288.

Imperial College of Science and Technology, London, Computational Fluid Dynamics Unit, Room 440, M.E. Building, Exhibition Road, London SW7 2BX.
Correspondent: Prof. D. B. Spalding.

The work in this Unit is centered around the use of PHOENICS, a general purpose computer program for multi-dimensional one- and two-phase flow. Applications in the two-phase flow area include research on the rewetting of hot surfaces, the impingement of droplets on (simulated) fuel rods in nuclear-reactor refill, the unsteady motion of a compressible gas containing solid particles (with emphasis on determining inter-phase friction and turbulent mixing laws) and on Rayleigh–Taylor instability in the mixing of two initially separated phases under the influence of a body-force gradient. The latter study is also being pursued experimentally. The Unit is further developing procedures for the computation of the flow of two interpenetrating phases, with extension to turbulence.

Exploitation of the PHOENICS code in the commercial sphere is being pursued by CHAM Ltd. (Wimbledon, U.K.). The CHAM work includes PWR studies, combustion studies, particle deposition in cyclones and duct bends, avalanches, fast breeder reactor problems etc. In the work on PWR, the PHOENICS code is being used for studies of reflood, for simulation of LOCA behaviour for the complete system, for studies of non-uniformities in the reactor core and for two and three dimensional studies of steady and unsteady flow in full-scale and model steam generators. The combustion work includes the use of PHOENICS and its satellites for computer simulation of flow phenomena involving gases and fuel particles in a variety of systems including rockets and coal combustors.

Illustrative papers

MALIN, M. R., MARKATOS, N. C., TATCHELL, D. G. & SPALDING, D. B. 1982 Analysis and computation of multi-dimensional coal combustion processes. Presented at the *AIAA/ASME 3rd Joint Thermophysics, Fluids, Plasma and Heat Transfer Conf.*, Saint Louis, Missouri, 8–11 June 1982. ASME82-FE-8.

MARKATOS, N. C. G., MOULT, A., PHELPS, P. J. & SPALDING, D. B. 1979 Calculation of steady, three-dimensional, two-phase flow and heat transfer in steam generators. *Proc. Int. Centre for Heat and Mass Transfer Seminar: Two Phase Momentum, Heat and Mass Transfer* (Edited by F. DURST, G. TSIKLAURI & N. AFGHAN), Vol. 1, pp. 485–502. Hemisphere, New York.

NILMANI, M., MAXWELL, T. T., ROBERTSON, D. G. C. & SPALDING, D. B. 1981 Prediction of initial motion of a gas bubble in liquids. *Appl. Math. Model* **5**, 24–28.

SPALDING, D. B. 1981 A general purpose computer program for multi-dimensional one- and two-phase flow. Presented at *Lehigh IMACS Conf.*, July 1981, published in *Math. Comput. Simulation* **XXIII**, 267–276.

Imperial College of Science and Technology, London, Department of Chemical Engineering and Chemical Technology, Prince Consort Road, London SW7 2BY.

Correspondents: Dr. G. H. Anderson, Dr. M. Streat and Prof. F. J. Weinberg.

This department is carrying out extensive work over a whole range of multiphase flow problems, including gas–liquid, liquid–liquid, liquid–solid and gas–solid systems.

The work on *gas–liquid* flow includes studies of foaming in distillation columns, studies of the dispersion of matter in two-phase flow through porous masses and entrainment of gases into liquid spray systems. In the foaming studies, the fundamental mechanism of foam collapse are being evaluated on the basis of interfacial property measurements. The results of this work will then be used to develop a model for foam collapse in downcomers in distillation columns. The outcome of the work will provide guide-lines as to how to design columns to avoid limitations due to foaming. The work on spray systems has been proceeding for many years in the Department and the Department has participated in the formation of an International Institute for Atomization Spray Systems which will hold its 3rd conference in London in 1985.

In the *liquid–liquid* flow area, the work includes studies of *capillary hydrodynamics*, specifically the study of the dynamic contact angles which are displayed as a liquid–liquid interface moves along a solid surface. Interference microscopy is employed to examine these contact angles at a distance of about 10^{-5} m from the three-phase contact line with the aim of theoretically modelling the system.

The work on *liquid–solids* systems includes studies of *anaerobic fermentation* in fluidized beds and work on *hydraulic transportation.* The anaerobic fermentation work includes fundamental studies on immobilization techniques, reactor design and performance at a pilot scale. In the hydraulic transportation work, experiments have been performed in 1-in. and 3-in. dia. pipe lines to study the frictional pressure drop for hydraulic transportation of glass Ballotini, fine sand, gravel and iron ore at in-line concentrations of 45–55% by volume solids. Transportation at high concentration reduces wear and attribition in the moving parts and minimises dewatering of the solid product. Hydraulic conveying is relevant to the disposal of medium and low active solid nuclear waste material and experiments have been performed in a 4-in.-dia. pipe rig at the UKAEA Winfrith laboratory to study the hydraulic conveying of magnesium and aluminium platelets in the size range 0.2–2.0 cm. In a related study, solid–liquid separation mechanisms in hydrocyclones are being investigated. Experiments are in progress to produce flocs capable of withstanding high shear forces in a hydrocyclone.

The Department has a long tradition of research in combustion. Work in this area relevant to two-phase systems includes studies of combustion in *spouted and fluidized beds.* Closely associated with combustion work are studies of *particulate formation* associated with the oxidation of sulphur-dioxide and the development of *optical methods.* These latter methods include direct determination of particular size distribution and particular velocity using laser Doppler anemometry, deduction of size distribution of aerosols from light-scattering data and the use of spectral transparency methods for smaller droplet sizes.

Illustrative papers

ARBIB, H. A., SAWYER, R. F. & WEINBERG, F. J. 1981 The combustion characteristics of spouted beds. *Proc. 18th Symp. (Int.) on Combustion,* The Combustion Institute, pp. 233–241.

EISENKLAM, P. 1976 Recent research and development work on liquid atomization in Europe and the U.S. *Keynote Paper, 5th Conf. Liquid Atomization,* Tokyo.

TELEVANTOS, Y., SHOOK, C., CARLETON, A. J. & STREAT, M. 1979 Flow of slurries of coarse particles at high solids concentrations. *Canad. J. Chem. Engng* **57**, 255–262.

WILSON, K. C., BROWN, N. P. & STREAT, M. 1979 Hydraulic hoisting at high concentration: A new study of friction mechanism. *Hydrotransport* **6**, BHRA, 1979, T.269.

WEINBERG, F. J. 1981 Combustion research: Imperial College. *Energy World,* February, pp. 5–9.

Imperial College of Science and Technology, Department of Mechanical Engineering, Exhibition Road, London SW7 2BX.

Correspondents: Prof. J. H. Whitelaw and Dr. R. I. Crane.

The two main areas of work in this department are concerned respectively with *two phase combustion systems* and with *dispersed flows.*

In the work on combustion, measurements have been made on velocity distributions, dropsizes, etc. in confined kerosene spray flames in the context of furnaces. This work has been done in conjunction with UKAEA Harwell and is aimed at improving furnace design methods. Similar research has been carried out with gas-turbine combustors, with open kerosene-spray flames and with mono-dispersed kerosene droplets. A new furnace has been constructed in the department which will burn coal and has, so far, operated with gas and with pulverized fuel. This latter work is sponsored by the Science and Engineering Research Council (SERC). In all of these experiments, laser-based methods (e.g. LDA) have been used to make local measurements. This allows detailed comparisons to be made with computer simulations (of the combustion and flow processes in furnaces) which are also being actively pursued by the Department. In the work on simulating droplet combustion, droplet models have been used in which the drops are allowed to travel with different velocities from the gas phase and also models where they do not.

The availability of sophisticated optical measurements has led the Department into experiments aimed at providing a fundamental knowledge of inter-phase interactions in two phase flow. Examples here are studies of *bubble-induced circulation* in a water filled enclosure (being carried out in conjunction with the University of Karlsruhe) and measurements of the influence of large solid particles in an air jet.

Studies are proceeding of dispersed systems (droplets, particles, aerosols). This work includes both experimental and theoretical studies. In the experimental work, the emphasis has been on the development of new image analysis techniques for particle size analysis. The analytical work has concentrated on numerical simulation methods for the motion of particles in channel flows. These models include the combined effects of particle coalescence and diffusional deposition and have been applied to both straight pipes and to flow around bends and turbines. In the case of flow in curved ducts, Görtler vortices are formed in the concave surface boundary layers and finite difference techniques were used to predict such flows; the calculated flow fields were included in a particle tracking procedure to predict the extent to which the Görtler vortices influence the inertial impaction deposition on the outer wall of a duct bend. In another theoretical programme a two-phase flow model is under development using time-marching techniques and incorporating two-way momentum and energy coupling between the phases. This latter work is linked to some studies of flow of air loaded with glass beads through a vertical nozzle. Particle size and velocity were measured in these experiments using double-flash photography and the results are being compared with the theoretical predictions.

Illustrative papers

BANHAWY, Y. E. & WHITELAW, J. H. 1980 Calculation of the flow properties of a confined kerosene-spray flame. *AIAA J.* **18**, 1503-1510.

CRANE, R. I. 1982 Drop coalescence and deposition in turbulent wet steam pipe flows. *Int. J. Heat Fluid Flow* **3**, 13–20.

CRANE, R. I. & EVANS, R. L. 1977 Inertial deposition of particles in a pipe bend. *J. Aerosol Sci.* **8**, 161–170.

FOUNTI, M., WHITELAW, J. H. & HUTCHINSON, P. 1980 Measurements of the kerosene-fuelled flow in a model furnace. *J. Energy* **4**, 273–278.

OW, C. S. & CRANE, R. I. 1980 A simple off-line automatic image analysis system with application dropsizing in two-phase flows. *Int. J. Heat Fluid Flow* **2**, 47–53.

University of Leeds, Department of Mechanical Engineering, Leeds, LS2 9JT.

Correspondent: Dr. F. R. Mobbs.

The work in this department is concentrated on various aspects of *gas–solid flow.* The work includes the effect of solid particles on *aerodynamic noise generation* in turbulent flows, *supersonic gas–solid flow* and *inertial filtration.* In the first of these areas, measurements of overall sound pressure level and noise frequency spectrum have been made with a view to developing methods of solid mass flow metering and in-stream particle size analysis. A detailed study of the effect of particles on the spreading of turbulent jets is also in progress.

The studies of supersonic gas–solid flow include measurements of the effect of solid particles on shock speed and shock attenuation and studies of two-phase supersonic flow at forward and rearward facing steps and around wedges. The particle-in-cell numerical technique has been extended to these two phase flow situations.

The inertial filtration studies involve measurements of the efficiency of louvered inertia air filters and numerical modelling of the flows through them. Effect of varying geometry on efficiency and pressure loss has been studied.

Illustrative papers

El-Shorbagy, K. A., Mobbs, F. R. & Cole, B. N. 1981 Solid phase metering in two-phase flow using aerodynamic noise. *Int. Conf. Advances in Flow Measurement Techniques*, Warwick, 9–11 September, Paper F3.

Ibrahim, K. A., Mobbs, F. R. & Cole, B. N. 1982 The development of detached shock waves in gas-solid suspension flow. *AIAA/ASME Joint Fluids, Plasma, Thermophysics Heat Transfer Conf.*, Saint Louis, Missouri, June.

Poulton, P., Cole, B. N. & Mobbs, F. R. 1981 An experimental and numerical investigation of louvred inertia air filter performance. *I. Mech. E. Conf. Gas-born Particles*, July 1981, Oxford, Paper C82.

University of Liverpool, Department of Mechanical Engineering, P.O. Box 147, Liverpool L69 3BX.

Correspondent: Dr. D. J. Ryley.

The two phase flow work in this department is currently concentrated in three main areas, namely *wet steam turbine flows, geothermal studies* and *contact angle studies.* The work on steam turbines has been proceeding for many years. At some point within the low-pressure stages of a steam turbine, the steam nucleates forming fog droplets of size 0.01–1.0 μm which invade the boundary layer, are deposited by diffusion and form liquid rivulets which are propelled to the blade trailing edge. This liquid is swept into entrainment in the blade wakes and broken into fragments which cannot follow the vapour streamlines due to inertia and which erode the succeeding moving blades. The work at Liverpool is aimed at simulating the drop motion and deposition using aerosol–air mixtures. The aerosols are of a soluble fluorescent dye which can later be removed from the surfaces and its deposition rate determined by fluorimetric techniques. The studies here include the effects of thermophoresis.

In the work on geothermal wells, a computer prediction method has been developed for calculating pressure, dryness and void fraction profiles up the well and has been compared to actual well data.

The work on contact angle includes the development of a new method for determining contact angle based on the shape of a sessile drop on a horizontal surface, the evaluation of the shape of sessile drops on inclined surfaces and, more recently, measurements have been made of the energy loss during the breakdown of a liquid film. In this latter experiment, a liquid film was formed on a glass block whose surface had been treated to give some areas which are wetted by water and others which are water repellent. When the film perforates, there is an energy loss.

Illustrative papers

Ryley, D. J. & Khoshain, B. H. 1977 A new method of determining the contact angle made by a sessile drop upon a horizontal surface. *J. Colloid Interface Sci.* **59**, 243–251.

Ryley, D. J. & Ismail, M. S. B. 1978 The shape of sessile water drops on inclined plain surfaces. *J. Colloid Interface Sci.* **65**, 394–396.

Ryley, D. J. & El-Shobokshy, M. S. 1978 The deposition of fog droplets by diffusion onto steam turbine guide blades. *Proc. 6th Int. Heat Transfer Conf.*, Toronto, August 1978, **2**, Paper EC-14, pp. 85–90.

Ryley, D. J. & Loftus, F. P. 1980 An investigation of electostatic phenomena associated with flowing wet steam with particular reference to the wet steam turbine. *Int. J. Heat Fluid Flow* **2**, 77–84.

Ryley, D. J. & Parker, J. G. 1982 Flowing geothermal wells; Ceero Prieto Well M.91 and Krafla Well KJ-9.1; compared with experimental data. *Int. Conf. Geothermal Energy*, Florence, Italy, May, Paper C4.

University College, London, Department of Chemical and Biochemical Engineering, Torrington Place, London WC1E 7JE.
Correspondent: Prof. P. N. Rowe.
The main work on two-phase flow systems in this department is concerned with *fluidized beds* and *crystallization systems.*

The department has a long history of work in fluidization and current studies include X-ray visualization of fluidized beds, fluidization at pressures up to 100 atm, studies of chemical reaction, entrance effects, particle mixing, granulation flocculation, etc. There is also a great deal of emphasis in the department on studies of chemical reactions and catalysis in fluidized beds and on fluidized bed combustion. This latter work includes combustion systems for biomass and is linked closely with the department's main area of work on biochemical engineering.

A wide range of studies are being carried out in the crystallization area including the influence of impurities in nucleation and crystal growth, studies of precipitation and salting-out, formation of liquid inclusions in crystals, design of full-scale crystallizers, mechanics of sieving and screening and the effects of diffusion and mass transfer on crystallization.

Illustrative papers

NIENOW, A. W. & NAIMER, N. S. 1980 Continuous mixing of two particulate species of different density in a gas fluidized bed. *Trans. Inst. Chem. Energy* **58**, 181–186.

ROWE, P. N. & MASSON, H. 1980 Fluidized bed bubbles observed simultaneously by probe and by X-rays. *Chem. Engng Sci.* **35**, 1443–1447.

SMITH, P. G. & NIENOW, A. W. 1981 Growth mechanisms in fluidized bed granulation. Proc. Conf. on Particle Technology, Birmingham, March, *I. Chem. E. Symp.* Ser. No. 63, D2/K1-14.

TAVARE, N. S. & GARSIDE, J. 1980 Analysis of batch crystallizers. *Ind. Engng Chem. Process Des. Dev.* **19**, 653–665.

YATES, J. G., MACGILLIVRAY, M. & CHEESMAN, D. J. 1980 Coal devolatisation in fluidized bed combustors. *Chem. Engng Sci.* **35**, 2360–2361.

University of Manchester, Simon Engineering Laboratories, Oxford Road, Manchester M13 9PL.
Correspondent: Dr. M. J. Watts.
The main emphasis of the work at Manchester is on problems associated with transient boiling phenomena in the context of nuclear reactor safety. This includes studies of *film boiling in forced convection*, studies of *rewetting of hot surfaces*, investigations of *homogeneous nucleation* in transient boiling and work on *flow boiling critical heat flux* during flow reversal and at high pressure.

The work on forced convective film boiling includes studies on film boiling on a sphere immersed in subcooled or superheated liquids, with particular emphasis on the stability of such film boiling; this is important in the context of fuel-coolant-interaction (FCI) which may lead to vapour explosion in certain postulated nuclear reactor accidents.

The experiments on hot surface rewetting were carried out using liquid sodium and the first series of tests were done at low- (sub-atmospheric) pressure conditions to reduce the required temperatures. A new study is now beginning in which pressures near atmospheric will be employed which implies sodium temperatures of up to 900°C. Heater rod surface temperatures of up to 1200°C are envisaged.

The Laboratories have a long term interest in transient boiling. At very high heating rates (up to 10 million K/s), nucleation occurs preferentially in a homogeneous rather than a heterogeneous manner. Heat fluxes in excess of 100 MW/m^2 are observed immediately subsequent to homogeneous nucleation; again such results have great significance in the context of fuel-coolant interactions in nuclear reactors.

The Manchester team have been very much involved in studies of supercritical heat transfer and have extended this work to the study of buoyancy effects leading to the suppression of turbulence and laminarisation of the flow. Similar effects are observed at high sub-critical pressures and experimental work is proceeding on the study of upward and downward flow boiling at low velocities under such conditions. Studies are also proceeding on critical heat flux during a flow reversal in the boiling of water at atmospheric and high pressure. Similar work is proceeding also on upward and downward flow boiling with carbon-dioxide at high subcritical pressure.

Illustrative papers

DEREWNICKI, K. & HALL, W. B. 1982 Homogeneous nucleation in transient boiling. *Proc. 7th Int. Heat Transfer Conf.*, Munich, September, **4**, Paper B82, pp. 9–14.

DICKSON, J. & WEY, B. O. 1981 Experimental study of the rewetting of a hot surface by sodium. *Nucl. Energy* **20**, 311–317.

HALL, W. B. 1976 Heat transfer problems in nuclear reactor safety. *Proc. Inst. Mech. Engng* **190**, 215–224.

HALL, W. B. & JACKSON, J. D. 1978 Heat transfer near the critical point. *Proc. 6th Int. Heat Transfer Conf.*, Toronto, Canada, August **6**, pp. 377–392.

National Engineering Laboratory, Heat Business Centre, East Kilbride, Glasgow, G75 0QU.
Correspondent: Dr. T. J. S. Brain.

NEL has a long tradition of work in two phase flow. Current work includes *pressure drop in fittings and tube bundles, phase content (void fraction) in heat exchangers and ideal tube bundles, momentum flux measurements* and studies of *nonequilibrium two phase flow.*

Study of pressure drop in pipes and pipe line fittings continues to be a major interest at NEL and a new Freon loop is presently being constructed from 76 mm i.d. piping and comprises a 9-m vertical section followed by a horizontal section measuring up to 24 m in length. Pressure drop is also being studied in a model heat exchanger constructed of transparent plastic which allows the observation of the flow patterns. Methods of predicting flow pattern and pressure drop have been developed.

Void fraction (or liquid holdup) is being measured in both a model heat exchanger and also in ideal tube banks. A quick-closing valve method (employing pneumatically operated plates) has been designed for operation on these systems and data have already been obtained for a range of mass flows and qualities.

Measurements of momentum flux and void fraction at atmospheric and sub-atmospheric pressures have been carried out for air-water flows in horizontal pipes. A momentum flux meter was specially designed and void fraction measured simultaneously. Recently, an analytical model has been developed for critical two-phase flow based on a relaxation model for predicting non-equilibrium effects. The model is particularly suitable for the sub-cooled, saturated and low-quality fluid states.

The Heat Business Centre at NEL is one of the partners (with UKAEA Harwell) in the operation of Heat Transfer and Fluid Flow Service (HTFS). This Service provides data and design methods for industry and has a number of proprietary projects in the two phase flow area, particularly in the boiling and condensing field.

Illustrative papers

CHISHOLM, D. 1979 Two phase flow in bends. *Int. J. Multiphase Flow* **6**, 363–367.

CHISHOLM, D. 1981 Flow of compressible two-phase mixtures through sharp-edged orifices. *J. Mech. Engng Sci.* **23**, 45–48.

GRANT, I. D. R., CHISHOLM, D. & COTCHIN, C. D. 1980 Shellside flow in horizontal condensers. ASME Paper No. 80-HT-56.

HENRY, J. A. R. 1981 Dividing annular flow in a horizontal tee. *Int. J. Multiphase Flow* **7**, 343–355.

HENRY, J. A. R., MORRIS, S. D. & MACDONALD, A. M. 1982 Momentum flux during sub-atmospheric two-phase flow through a pipe. *Proc. 7th Int. Heat Transfer Conf.*, Munich, September, **5**, Paper TF18, pp. 293–299.

National Engineering Laboratory, Hydrocarbon Flow Measurement Business Centre, East Kilbride, Glasgow G75 0QU.
Correspondent: *Dr. W. C. Pursley.*

The main emphasis of the work in this Business Centre at NEL has been concerned with flow measurement problems in *liquid/liquid flow*. The application here has been the measurement of water content of crude oil and the original work arose from the U.K. Department of Energy's requirements for a knowledge of the behaviour of commercial samplers in use in the North Sea. NEL have constructed a liquid–liquid flow loop and have carried out evaluation tests of a number of commercial flow samplers.

The Business Centre is currently engaged in a research programme for a consortium of sponsors in which the behaviour of water droplets in the vicinity of sampler probes will be investigated under a variety of conditions. The use of isokinetic sampling and studies of the behaviour of water/oil mixtures in vertical pipes will be included. The Business Centre also undertakes work for specific clients though the results are, of course, proporietary to those clients.

In the *gas–liquid* flow area, work has been sponsored at Strathclyde University (see below) on flow measurement and pressure drops in pipes, orifices and gate valves.

Illustrative papers

ANON 1979 A resume of the investigations into automatic sampling techniques for water-in-oil mixtures. NEL Rep. 149/79 (Y4/DEY/1).

GRATTAN, E., ROONEY, D. H., & SIMPSON, H. C. 1981 Two phase flow through gate valves and orifice plates. NEL Rep. No. 678.

PURSLEY, W. C. & HUMPHREYS, J. S. 1981 Representative sampling from crude oil/water mixtures. *Symp. Automatic Sampling and Water Determination for Crude Oils*, Maidstone, Kent, November.

SIMPSON, H. C., ROONEY, D. H., GRATTAN, E. & AL-SAMARRAE, F. A. A. 1981 Two phase flow studies in large diameter horizontal tubes. NEL Rep. No. 677.

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Correspondent: *Dr. P. B. Whalley.*

The department has carried out a wide range of studies in boiling heat transfer and two phase flow; recently, it was awarded a Special Research Grant by the Science and Engineering Research Council (SERC) for a programme of work in these areas in collaboration with UKAEA Harwell. The longest established programmes in the department are those on *heat and mass transfer in nucleate boiling* and on *cryogenic heat transfer systems*. More recently, work has commenced on *adiabatic two-phase flows* and other work is proceeding on *noise generation* due to pressure fluctuations in two phase flow.

In the work on heat and mass transfer in nucleate boiling, studies have been proceeding on bubble nucleation in zero gravity situation, the generation of successive bubbles in normal gravity, bubble generation in binary liquid mixtures, liquid flow effects on bubble nucleation and the developments of correlations for nucleate boiling heat transfer. Other studies include boiling on porous surfaces, mixture boiling in tubes, nucleate boiling studies relating to PWR safety and on the mechanism of annular flow boiling.

The adiabatic two phase flow studies (carried out in collaboration with UKAEA Harwell) include simultaneous measurement of wall shear stress and liquid film thickness in annular flow, studies on flow in T-junctions and studies of the effect of wall disturbances on two phase flows.

The cryogenic work includes studies of boiling of cryogenic fluids and studies of the instabilities occurring in thermosiphon systems in which cryogenic fluids are evaporated. This latter work is also applicable more generally to other two phase flow instability problems.

Illustrative papers

Cooper, M. G. & Stone, C. R. 1981 Boiling of binary mixtures—study of individual bubbles. *Int. J. Heat Mass Transfer* **24**, 1937–1950.

Franklin, R. E. & MacMillan, J. C. 1980 Noise generation in cavitating flows. Oxford University Engineering Laboratory Rep. No. 1312.

Hands, B. A. 1979 The flow stability of a liquid nitrogen thermosiphon with 8 mm bore riser. *AIChE Symp. Ser.* **75**(189), 177–184.

Kenning, D. B. R. & Del Valle Munoz, V. H. 1981 Fully developed nucleate boiling: Overlap of areas of influence and interference between bubble sites. *Int. J. Heat Mass Transfer* **24**, 1025–1032.

Whalley, P. B., Azzopardi, B. J., Hewitt, G. F. & Owen, R. G. 1982 A physical model for two phase flows with thermodynamic and hydrodynamic non-equilibrium. *Proc. 7th Int. Heat Transfer Conf.*, Munich, September, **5**, Paper Cs29, pp. 181–188.

Queen Mary College, London, Department of Mechanical Engineering, Mile End Road, London E14NS.

Correspondent: Dr. J. W. Rose.

The work in this department is concerned principally with *condensation heat transfer* and with the effects of various factors upon it. The emphasis has been on making extremely accurate measurements of condensation systems using specially developed techniques. Typical of the recent studies are those on the effect of non-condensing gas on film condensation, the effect of vapour velocity on film condensation, interface mass transfer, dropwise condensation and condensation on finned tubes.

A new theory for the effect of non-condensing gas on film condensation has been checked out by recent measurements for flow of various vapour–gas mixtures over horizontal tubes. The model appears to be accurately validated and can be combined with suitable equations for the heat transfer across the condensate film to predict the combined resistance in condensation. The film resistance in condensation is affected by vapour velocity and the Department has produced a new model for this effect for condensation on horizontal tubes. New data obtained in the Department show the heat transfer coefficient significantly exceeds that predicted by the theory and work is continuing to investigate this.

The difference between the net condensation and evaporation rates which occurs at a liquid–vapour interface gives rise to a small, but sometimes significant, temperature difference across the interface itself. Early work suggested that the *accommodation* or *condensation* coefficient for this process was rather low under some circumstances but modern measurements tend to show that it is close to unity. The Department has carried out very accurate measurements for condensation of mercury (where the interface resistance is more significant) and shows that the condensation coefficient is very near to unity and certainly exceeds 0.9. The data also show that the linear theories for interface mass transfer are only valid in the low condensation rate limit. The new data were in general agreement with a recently published theory which predicts this effect.

The Department has carried out extensive work on *dropwise condensation*, carrying out experiments with steam, mercury and (more recently) with ethanediol. For complex molecules (like ethanediol) it is necessary to correct the conventional theories for interphase pressure difference to take account of the difference between the ordinary and volume viscosities.

Another recent study on dropwise condensation has concerned the transition from dropwise to filmwise condensation as cooling intensity increases. The heat transfer data showed that the transition sets in at a microscopic level; i.e. the heat transfer coefficient begins to decrease strongly with increasing cooling intensity though the appearance remains that of an ideal dropwise condensation.

Preliminary studies have been carried out on the condensation of steam on single horizontal integral finned tubes. Vapour-side enhancements (ratio of vapour-side coefficients to plain tube value) of up to around 5 were obtained and these are significantly greater than that anticipated on the basis only of the area increase. A graph of enhancement against fin spacing shows local reproducible maxima and minima.

Illustrative papers

LEE, W. C. & ROSE, J. W. 1982 Film condensation on a horizontal tube–effect of vapour velocity. *Proc. 7th Int. Heat Transfer Conf.*, Munich, September, **5**, Paper Cs17, pp. 101–106.

NIKNEJAD, J. & ROSE, J. W. 1981 Interphase matter transfer: experimental study of condensation of mercury. *Proc. Roy. Soc.* **A378**, 305–327.

ROSE, J. W. 1976 Further aspects of dropwise condensation theory. *Int. J. Heat Mass Transfer* **19**, 1363–1370.

ROSE, J. W. 1980 Approximate equations for forced-convection condensation in the presence of a non-condensing gas on a flat plate and horizontal tube. *Int. J. Heat Mass Transfer* **23**, 539–546.

STYLIANOU, S. A. & ROSE, J. W. 1980 Dropwise condensation on surfaces having different thermal conductivities. *J. Heat Transfer* **102**, 477–482.

Queen Mary College, London, Department of Nuclear Engineering, Mile End Road, London E1 4NS.

Correspondent: Prof. D. C. Leslie.

The work in this department includes studies of *two phase flow codes* for LWR safety, studies of *burnout in convective flow through rod clusters* and studies of the flow in a *particle-laden free jet.*

Generalized codes for two phase flow are an important tool in assessing the safety of light water reactors (LWRs). The objective of the project in the Department (which is sponsored by the UKAEA) is to validate codes such as TRAC and RELAP against simple and well defined experiments, and testing the effect of model changes on such codes.

The experiments on *burnout in convective flow* were done using Freon using clusters with 3, 4, 5 and 6 heated rods on the peripheral circle and one heated or unheated rod in the center. Important differences were found for the even and odd clusters and for the different flow regions. The burnout flux is higher for the odd geometry in the low flow (high quality) region whereas the opposite is true for the high flow region. Preparations are under way for a basic study of the effect of reflooding on burnout in very simple geometries, again using the Freon rig.

In the studies on *particle-laden free jets* the structure of a turbulent free air jet laden with solid particles (125 μm, 250 μm) has been studied for nozzle exit Reynolds numbers of 12,000 and 20,000. The field of primary air concentration and of solid particle concentration has been studied with a light-scatter technique. The velocity field of both phases has been studied by using a laser Doppler anemometer using frequency shift. The results obtained thus far indicate that in the initial region of the jet (up to 10 nozzle diameters) the intensity of fluid turbulence is increased by the particles whereas further down-stream, the intensity is decreased. Measurements of energy spectra of velocity and concentration fluctuations indicate that the particles cause a redistribution of turbulent energy from lower to higher frequencies.

Illustrative papers

Ali, S. S. 1981 Flow in a turbulent air jet laden with solid particles. Ph.D. Thesis, University of London.

Berger, F. P. & Akaho, E. A. K. 1982 Effect of rod bundle geometry (even-odd) on burnout. *Proc. 7th Int. Heat Transfer Conf.*, Munich, September, **4**, Paper No. FB16, pp. 267–272.

University of Sheffield, Department of Chemical Engineering and Fuel Technology, Mappin Street, Sheffield S13 JD.

Correspondent: Prof. J. Swithenbank.

This Department is best known for its work on combustion systems and the main thrust has been towards the development of comprehensive combustor design algorithms for a range of industrial and propulsion applications; the design algorithms include accurate flow prediction methods and comprehensive combustion models. This work has led to a strong interest in the Department in a wide range of techniques (such as numerical modelling of turbulent flow/combustion field and the use of optical methods for velocity and particle size) which have been applied not only in the combustion area, but also in a number of other applications such as particle separators, cyclones, and crystallizers.

The mathematical modelling studies have included two phase swirling flows and two-phase confined vortex flows. In the latter case, it was shown that the widely used k–ϵ turbulence model is inapplicable, and a new model of turbulence has been developed which entails the solution of a set of algebraic equations for the individual Reynolds stresses in addition to the addition to the partial differential equations for the transport of turbulence kinetic energy and its dissipation rate. The models have been applied to cyclone flows, gas turbine flow, and diesel injector studies. In each of these cases, experimental data have been obtained using a back scatter laser Doppler system. In the gas turbine studies, residence time distribution has been measured using pulses of mercury vapour and in the diesel injector studies, work has been done on measurement of in-line particle holograms using an optical diffraction droplet sizer.

Another major area in the department's combustion work is that on fluidized bed combustion and this includes pollution studies, mathematical modelling of fluidized bed combustors, incineration of low heat content solid and liquid waste, combustion of coal in rotating fluidized beds, studies of combustion in pressurized rotating fluidized beds, incineration of oil refining tars, etc.

The department has traditionally had a strong interest in liquid spray combustion and this includes parametric studies of heavy fuel oil flames, laser anemometry studies, the development of laser diffraction particle sizing and its application to the study of fuel spray structure and studies of pneumatic atomization.

Other studies relating to particle mechanics and particle separation include studies of the handleability of coal finds, the flow of mixtures of large and small particles and fabric dust filtration. There is an extensive programme on coal combustion including studies of coal fired cyclone burners and of the combustion of coal–oil suspensions.

Illustrative papers

Ayers, W. H., Boysan, F. & Swithenbank, J. 1981 Three-dimensional droplet trajectories in gas turbine combustors. *5th Int. Symp. Airbreathing Engines*, February, Bangalore, India.

Ayers, W. H., Boysan, F. & Swithenbank, J. 1982 Fundamental studies of two phase turbulent flows in cyclone separators. *Inst. Chem. Engng Jubilee Symp.* April, pp. G30–G34.

Boysan, F., Ayers, W. H., Swithenbank, J. & Pan, Z. 1980 Three-dimensional model of spray combustion in gas turbine combustors. *AIAA Meeting*, Saint Louis, January.

Yule, A. J., Seng, C. A., Felton, P. G., Ungut, A. & Chigier, N. A. 1981 A laser tomographic investigation of liquid fuel sprays. *Proc. 18th Symp. (Int.) on Combustion*, The Combustion Institute, pp. 501–1510.

YULE, A. J., SENG, C. A., FELTON, P. G., UNGUT, A. & CHIGIER, N. A. 1982 Sprays, drops, dust and particles: A study of vapourizing fuel sprays by lazer techniques. *Combus. Flame* **44**, 71–84.

University of Strathclyde, Glasgow, Department of Thermodynamics and Fluid Mechanics, Montrose Street, Glasgow G1, Scotland.
Correspondent: Dr. D. H. Rooney.

In addition to general studies on *gas–liquid flows*, the department is extensively involved in studies relating to *nuclear reactor safety*. The general studies include measurements on two phase flow in large diameter tubes including flow pattern prediction, pressure drops in pipes, bends, valves, orifices, etc. Work is proceeding on void fraction prediction and on the metering of two phase flows. There has been particular emphasis on prediction of the transition between flow patterns, and this had led to an interest in the development of flow pattern sensors.

The work related to *nuclear reactor safety* includes experimental and computational studies on loss-of-coolant accidents (LOCAs). Studies have been made of bypass conditions and methods of injection in emergency core coolant systems including hot and cold leg injection.

Apparatus has been constructed to simulate reactor refill, employing both air/water and steam/water systems. Theoretical and experimental work has been carried out on transient effects on drums, downcomer and riser tubes and this has been backed up by experimental studies using both water and Freon rigs on boiling heat transfer (vertical and horizontal flows), direct contact condensation and thermal nonequilibrium, and on formation and collapse of steam bubbles in water.

Other two phase studies being carried out in the Department include those on the effect of rapid drops in system pressure on *boiler circulation*, heat transfer from *extended surfaces* to air–water mixtures and, in the *condensation* area, studies of droplet separation from tubes and of the effect of inundation on condensation.

Illustration papers

ROONEY, D. H., SIMPSON, H. C. & MEGAHED, M. 1982 Non-equilibrium effects during refill in a pressurized water reactor. *European Two-Phase Flow Group Meeting*, Paris, 1982, Paper No. 2, Session 2. Phase Flow Group Meeting, Paris, 1982, paper No. 2, Session 2.

SIMPSON, H. C., ROONEY, D. H. & CALLANDER, T. M. S. 1979 Transient two-phase flow in a forced circulation Freon test rig. *Proc. Symp. Boiler Dynamics Control in Nuclear Power Stations*, BNES London, pp. 77–85.

SIMPSON, H. C., BEGGS, G. C. & FANNAR, H. 1982 The condensation of vapour bubbles in an immiscible liquid. *Proc. 7th Int. Heat Transfer Conf.*, Munich, **5**, Paper Cs3, pp. 15–20.

SIMPSON, H. C., ROONEY, D. H. & MEGAHED, M. 1981 The upward flow of air between two waterfalls: An unusual choked flow problem. *Int. J. Multiphase Flow* **7**, 129–149.

SIMPSON, H. C. & ROONEY, D. H. 1980 An investigation of flooding phenomena in an experiment relating to the PWR problem. *Proc. ANS/ASME/NRC Int. Topical Meeting on Nuclear Reactor Thermal-Hydraulics*, Saratoga Springs, New York, October, NUREG/CP-0014, **2**, pp. 1217–1236.

University College of Swansea, Department of Chemical Engineering, Singleton Park, Swansea SA2 8PP, Wales.
Correspondent: Prof. J. F. Richardson.

This department has had a continuing interest in transportation of materials in general, and fine particles in particular. Most of the recent research efforts have been concentrated on investigating the isothermal *two-phase co-current flow of air and liquids* in horizontal and vertical pipe lines. The department has two $1\frac{1}{2}$-in. nominal diameter pipe test rigs, one horizontal and the other vertical. In addition, the department has access to large diameter pipe lines

(4-in.–8-in.) and associated test facilities. Measurements can be made in the rigs of both pressure drop and liquid (or gas) holdup.

In recent years, the experimental work has been primarily concerned with the characteristics of particulate suspensions and of aqueous solutions of high molecular weight polymers and with the effect of injecting air into the flowing liquid. All of the fluids used display one of the commonest types of *non-Newtonian* behaviour, namely a viscosity which decreases with flow rate. The injection of air into these liquids during a flow in a pipe results in a *substantial reduction in frictional losses* provided the liquid is in laminar flow prior to air injection, so that the two phase pressure drop is less than that for the liquid flowing on its own at the same volumetric flow rate. This drag reduction phenomenon is observed in both the vertical and horizontal configurations, provided due consideration is given to the gravitational component in the vertical flow. In certain cases, a reduction in frictional losses of up to 80% can be observed in a horizontal pipe line. Thus, a given flow rate may be obtained for a much lower maximum pressure at the discharge of the pump or, alternatively, for a given pressure at the pump delivery, a greater flow rate of liquid may be obtained. A semi-empirical equation has been developed for prediction of maximum possible drag reduction. A useful by-product of this research has been the accumulation of a voluminous data bank of values of in-situ liquid holdup and, using this, a new predictive equation has been developed for the estimation of average liquid holdup in horizontal as well as vertical two phase flow of air with liquids exhibiting both Newtonian and non-Newtonian behaviour.

In the future, a new project is planned concerned with the hydraulic conveying of coarse particles in shear-thinning suspensions of fines and/or aqueous polymer solutions. Such materials exhibit a lower apparent viscosity in the wall region where the shear rate is high and therefore the pressure gradient rises only slowly with velocity under laminar flow conditions. However, elsewhere in the pipe where the shear rate is low, the apparent viscosity is high and thus the suspension of particles is facilitated. Such fluids therefore offer an attractive alternative to water as conveying media for pipe-line transport.

Illustrative paper

FAROOQI, S. I., HEYWOOD, N. I. & RICHARDSON, J. F. 1980 Drag reduction by air injection for suspension flow in a horizontal pipeline. *Trans. Inst. Chem. Engng* **58**, 16–27.

FAROOQI, S. I. & RICHARDSON, J. F. 1980 Rheological behaviour of kaolin suspensions in water and water-glycerol mixtures. *Trans. Inst. Chem. Engng* **58**, 116–124.

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This laboratory has a long tradition of work on two phase *gas–liquid* flow and *boiling*. The work started and continues in the context of nuclear reactor thermal hydraulics but, from the late 1960s, the Division has been strongly involved in the non-nuclear area through its operation (jointly with NEL) of the Heat Transfer and Fluid Flow Service (HTFS) and the Separation Processes Service (SPS). This had led the Division into a wide range of areas of two phase flow and boiling and, in the content of SPS, there is interest in problems of *gas–solid* flows, particularly with respect to drying and gas cleaning problems.

In the gas–liquid flow area, the main interest has been on the study of *annular flow* which is one of the most important types of flow, particularly in evaporating and condensing systems. Here, the emphasis has been on basic studies, and in particular on the interfacial structure (for instance, the creation and motion of *disturbance waves*) and on the creation, size, motion and deposition of liquid droplets in annular flow. A wide range of techniques have been developed to investigate these phenomena for systems at hydrodynamic and thermodynamic equilibrium and for systems where there are departures from both these equilibrium states. The main emphasis has been on flow in pipes, but extensive studies have also been done for two phase flow in T-junctions in venturi scrubbers, on flow in tube banks, etc.

Closely associated with the work on two phase hydrodynamics have been the studies on boiling. In recent years, this has concentrated on the boiling of multicomponent fluids, reflecting the increasing non-nuclear industry emphasis of the work. Up to now, this work has concentrated on ethanol, cyclohexane and their mixtures. Data taken in a 26-mm-dia. tube suggest that nucleate boiling is dominant at qualities up to 30% and that established correlations cannot cope, due presumably to their poor prediction of nucleate boiling.

Work is also proceeding in the Division in the condensation area where studies are being formed, as part of the HTFS programme, on condensation in cross flow over tube banks and in flow through both vertical and horizontal tubes. Again, emphasis has been on multi-component mixtures and the development of methods for predicting these accurately.

Gas–solid flows were studied in the context of pneumatic conveying dryers. The experiments showed that the Isolated Particle Model, used in all previously published models of pneumatic conveying, yielded much higher values of particle velocity in the channels than were found experimentally. Better agreement is obtained if account is taken of the retarding effect of particle-wall collisions. In a joint project with the University of Oxford, it is intended to use numerical modelling techniques to study momentum, heat and mass transfer in spray dryers. These start off as gas–liquid flow systems and then transpose into gas–solid system when the particles solidify.

In the nuclear area, the emphasis has been on studying the transition and film boiling regimes with specially developed test-sections which allow measurements to be made of heat transfer coefficient at low mass flows and qualities.

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The two phase flow studies carried out in the Heat Transfer Laboratory of this Division are mainly in support of PWR safety. In addition, the Safety Analysis Group in the Division has a major programme of experimental and theoretical studies concerned with fuel-coolant interaction, and the effect of high energy release and missiles on structures. Winfrith is also a centre for the analysis of experimental work carried out in overseas laboratories which include in-pile experiments involving two phase flow of sodium and high pressure water and their vapour.

In the heat transfer laboratory the topics covered include reflood studies in a single tube rig (REFLEX) and in a cluster test facility (THETIS) together with associated analysis and model development. The latter tests are with highly ballooned geometries typical of the state of a reactor fuel following a LOCA. Also proceeding are steady-state PWR cluster critical heat flux measurements in the TITAN rig and transient dryout during depressurization in an electrically heated tube. Work is also proceeding on critical discharge at supercritical pressure of subcooled water through orifices of various shapes.

Included in the Winfrith programme on degraded core and Post-Accident Heat Removal (PAHR) is work on dryout in beds of particles immersed in water and studies of debris dispersion by gas jets. In the dryout studies, the effect of particle size, of layering and the influence of various remedial devices is being investigated.

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Warren Spring Laboratory has been involved in many aspects of two phase flow over the last two decades; the present work is related to the characterization and flow of *liquid–solid systems*. However, the Laboratory has been involved in research on *pneumatic conveying* for something over a decade. They developed and patented the "Pulse Phase" conveyor which is now manufactured in many countries; the conveying system was later developed for pulverized refuse and the Laboratory is presently planning to set up a multi-client project in this area sponsored by a number of industrial companies.

In the *hydraulic conveying* field, the work has included an assessment of methods for predicting design velocities for pipe lines, work on the transport of large (50 mm) particles, use of carrier media to support large particles, and the development of methods for transporting solids at very high concentrations. Experience has been gained with a range of materials including coal, colliery spoil, aggregates, and iron oxide.

Work has been done on the flow of gas/non-Newtonian liquid systems with particular reference to the reduction of pressure drop in paste pipe lines.

One of the major outstanding research areas in rheology is that concerning the flow properties of especially high concentration suspensions and the Laboratory is expected to continue its substantial effort in this area in the future. A multi-client project (Thick Liquids and Pastes-TLP) has been set up whose main aims are work on the flow of dispersions of paste in equipment and the transfer of materials by rollers and the deagglomeration of powders in liquids. These areas of great industrial importance as is demonstrated by the continuing success of the Warren Spring multi-client projects.

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