Int. J. Multiphase Flow Vol. 6, pp. 157–168
Pergamon/Elsevier, 1980. Printed in Great Britain

MULTIPHASE FLOW PREDICTION IN POWER-SYSTEM EQUIPMENT AND COMPONENTS

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Abstract—The special requirements are discussed which need emphasis when multiphase flows in equipment and components are to be predicted. These relate to:
(1) The presence of internal structure, resisting the flow.
(2) Thermal interactions with the metal and primary fluid.
(3) The presence of narrow restrictions, slowing convergence.
(4) The fitting of the grid to the geometry.
(5) The handling of gravity stratification.
(6) The prediction of the flow regime.
Of all those, it is the last that is in most need of increased attention.

1. INTRODUCTION

1.1 *Purpose of the present paper*

The task addressed in the present paper lies in the general field of numerical modelling of multiphase flows; but concerns those aspects of the subject which are of especial importance when the flows to be considered arise in complex pieces of engineering equipment, or components of engineering systems.

The steam-generator of a pressurised-water nuclear plant serves as a convenient example, and will receive attention in the paper; but similar problems arise within the nuclear reactor itself, and in such components as headers, pipe junctions, separators, etc.

In one sense, numerical modelling of multiphase flows is a single subject, exhibiting problems which are the same whether the flow exists in a pipe, a plenum, the natural environment or a complex engineering apparatus. However, the modelling of flows in equipment and components brings some features into greater prominence than others; and it is these which will be attended to here. The nature of the problems will be described; the currently available solution techniques will be indicated; preliminary judgement will be passed upon their satisfactoriness; and the need for further work will be either implicitly or explicitly revealed.

Because the problems to be discussed are rather specialised ones, and because the luxury of attending to them is permissible only after the prime difficulty of formulating and solving the differential and finite-difference equations has been overcome, the fact that the solubility of the equations is here being taken for granted may be overlooked. The curious discrepancy therefore needs to be noted between the literature which is concerned with "fundamental" (which usually means "one-dimensional") flow phenomena, and that which is concerned with "practical" (i.e. two- and three-dimensional) ones; surprisingly, expressions of doubt concerning solubility are more frequent in the former than in the latter.

Thus Stuhmiller (1977) and Banerjee & Hancox (1978) have questioned the validity of certain differential equations, because Lyczkowski *et al.* (1975) and Bryce (1976) experienced difficulty in solving them in simple cases. The fact that plausible solutions even for complex cases have now been obtained by other authors (Amsden & Harlow 1975, Moult *et al.* 1977 and Baghdadi *et al.* 1978) has not yet, curiously, been sufficient to dispel the doubts so engendered.

The task of dispelling those doubts is not the one which is addressed here. However, Kurosaki & Spalding (1979), Singhal & Spalding (1979) and Spalding (1979) described a method which has been successfully used to solve the equations; and the Los Alamos group has also described valid solution schemes (Amsden & Harlow 1975, Boudreau & Smith 1978 and Daly 1979). The author believes that sound and soluble differential equations have been formulated and solved, and that the doubts remaining are of a physical rather than a mathematical character, such as: What flow regimes arise? What are the appropriate interphase friction and heat-transfer laws? These are the problems that ought to achieve primary attention.

1.2 *Features in common between multi-phase and single-phase numerical modelling*

Since many of those who engage in numerical modelling of multiphase flows have entered the field directly, without prior experience of single-phase modelling, what these two subjects have in common (which is almost everything) is sometimes over-looked; and difficulties may achieve prominence in the multiphase literature which have already been obviated by single-phase workers.

Accordingly, it is useful to list the features which single- and multiphase modelling have in common, as follows:

(a) The domain of study is sub-divided into a finite number of cells.

(b) The application of the conservation principles for mass, momentum and energy to these cells, coupled with interpolation rules to connect the resulting terms with grid-point values of the dependent variables, leads to algebraic relations ("finite-difference equations") between these values for nearby clusters of grid points.

(c) In addition to these cluster-point equations, sufficient auxiliary relations exist to close the problem, for example the "equation of state" connecting pressure, temperature and density, and also certain equations representing boundary-condition information.

(d) A reliable iterative "guess-and-correct" solution procedure must be devised (more than one can exist; and an even greater number of incompletely reliable procedures can distract the attention of the scientific community!).

(e) The solution procedure, along with suitable sequences of instructions for accepting input data and printing out desired answers, must be embodied in an efficient computer code.

(f) Because the auxiliary relations referred to under (c) above ordinarily incorporate information of low reliability, the computed predictions may need extensive and systematic comparison with experimental data.

(g) As a consequence of such comparisons, improvements may be recognised as appropriate to the auxiliary relations, and even to the formulation of the problem (nature and number of equations solved; nature of input information).

With so much in common, the differences between multi- and single-phase modelling appear as minor details. This is especially so when the IPSA procedure (Spalding 1979) is employed; the difference resides almost entirely in the pressure-correction equation.

1.3 *Special features of numerical modelling of multiphase flow in equipment and components*

The present conference is concerned with multiphase-flow modelling of various kinds, and at both the "fundamental" and "applied" levels; but the present paper is directed towards the latter only. It is therefore useful to list what special features of the general subject are brought thereby into prominence. Six such features appear to be important; they are:

(1) The flow phenomena are much affected by the presence, within the domain of integration, of solid structural members of a semi-permeable character, such as arrays of rods or tubes, screens, baffles, tube support devices, etc. These have the effect of "resisting" the flow and thereby influencing its velocity distribution.

(2) Thermal interactions between these internal structures and the fluid under survey also require attention; indeed, if the tubes contain a second fluid (as in a steam generator for example), its temperature field, as well as that of the metal, requires to be computed.

(3) The internal structure often has the effect of nearly "pinching off" one region of the flow domain from another. This may seriously lower the rate of convergence of the numerical solution procedure, unless special convergence-enhancing devices are included.

(4) The geometry of the internal structure, and of the surrounding walls, must be adequately

represented by the "grid" of points and cells which provide the framework of the computation. The "fitting" of the grid to the geometry is often the most time-consuming part of the construction of a numerical model.

(5) The important role played by gravity in multiphase-flow problems, when the phase densities differ, often results in "gravity stratification", whereby liquid lies in the bottom half of a container, with vapour above it. This stratification simultaneously alleviates and intensifies the difficulty of making predictions, the first through the reduction of dimensionality which may be permissible, the second through the consequent introduction into the *horizontal*-direction momentum equations of terms associated with (vertical-direction) gravity.

(6) The special feature which presents the greatest difficulty is that the "flow regimes", i.e. which phase is dispersed in which, and how fine is the sub-division, are almost unknown; and, sometimes, this ignorance is laid at the door of the numerical modeller, rather than that of the experimental researcher.

The presented paper is a discussion of the above six special features. In each case, the problem will be adumbrated, some methods of solution will be presented briefly, and examples of their implementation will be referred to.

Readers requiring more detail are referred particularly to Singhal & Spalding (1979) and Spalding (1980).

2. THE PRESENCE OF INTERNAL STRUCTURES RESISTING FLUID FLOW

2.1 *The problem*

In steam generators for nuclear power plants, the tubes carrying the primary fluid (hot pressurised water), are extremely numerous. This means that, even when the numerical grid is unusually fine (e.g. 20×20 for half the cross-section), many tubes cross the horizontal surfaces of a single control volume.

Since the flow across any control-volume surface can be characterised by only one velocity for each phase, and since there is space in the numerical procedure for only one volume fraction and one enthalpy for each phase within the cell, it is clear that a far-reaching averaging process has to take place; and the tubes can be represented by only a few numbers, e.g. the fraction of volume which they occupy, the surface area which they expose to the secondary fluid, the resistances which they exert to flow of the secondary fluid in the three coordinate directions, etc.

The question is: how can the maximum realism be retained in the mathematical formulation, within the above constraints?

2.2 *The recommended method of treating internal structures*

A way in which internal structures resisting flow can be adequately represented is to act as though these structures are distributed uniformly through each of the cells in which they appear at all, occuping a definite fraction of volume and blocking the same fraction of area. The velocities which are held in store are then those which, when multiplied by the fluid density, the cell-surface area and the free-area fraction, give the rate of mass transfer into or out of the cell. These fractions are all that is needed to characterise the continuity-influencing effects of the internal structure.

The momentum-influencing effects are best represented by non-linear momentum-sink formulae, chosen so as to represent the best available knowledge about the pressure drop necessary to sustain flow at the prevailing velocity for each phase. These formulae can be as complex as knowledge warrants; and, of course, they give different values of the momentum sink per unit length, and per unit velocity difference, according to the direction which is in question. Thus, a baffle provides a large resistance to flow which is normal to it, but only a slight one to flow which is parallel to its plane.

This method was first applied by Patankar & Spalding (1974) to the modelling of a single-phase shell-and-tube heat exchangers, and later, by the same authors, to nuclear boilers (Patankar & Spalding 1978). In the latter case, although of course two phases were present in the shell, the equal-velocity presumption was made; this presumption reduces the computational task to that of solving for a *single*-phase fluid (i.e one with but a single set of velocity components) with large density variations.

Perhaps all the computer codes in actual use in the steam-generator industry employ this technique, which has also been widely used in the modelling of other fluid-flow phenomena; it can therefore be regarded as thoroughly established. Of course, the physical realism of the resuting predictions still depends entirely on the appropriateness of the resistance formulae which are supplied; and these are far from being well documented or validated.

2.3 *Some results*

Figure 1 presents some computations made by the URSULA code (Singhal & Spalding 1979) for the axial-velocity profiles along two radial lines in the U-bend region of a nuclear steam generator. It is seen that the profiles are different; and the differences are partly the result of the non-uniformities over the cross-section of the resistances exerted by the tubes.

It will be noted that the vapour velocity is everywhere greater than the liquid velocity; the reason is that "slip" is allowed between the phases: the vapour velocities are each computed from the appropriate separate momentum equations.

3. THERMAL INTERACTIONS WITH THE METAL AND THE PRIMARY FLUID

3.1 *The problem*

The enthalpies of the individual phrases in a structure-filled flow are easily computed when the heat-supply rates are known. They often *are* known when flow in the reactor core is in question, at least as far as the whole mixture is concerned (in what proportions the heat is divided between the gas and the liquid, on the other hand, is usually a matter of guess-work).

When a steam generator is to be modelled, however, the heat-flux distribution is one of the *out*comes of the computation; the *in*put is probably (for a steady-state flow) the *overall* heat supply rate, information about the distribution of primary-fluid flow into the tubes, and knowledge that all the primary fluid at the tube inlets has the same (albeit unknown) temperature.

If *unsteady* phenomena are to be modelled, the heat capacity of the solid structure (steam-generator tubes; nuclear-fuel elements; support members) also plays a part. There are then at least *four* temperatures to be computed at each location, in general: those of the vapour, of the secondary liquid, of the metal and (for the steam generator) of the primary liquid.

The presence of the thermally active internal structure has not merely increased the *magnitude* of the problem, it has also introduced a mechanism whereby convergence of the numerical solution can become excruciatingly slow. This occurs whenever the temperatures for secondary fluid, metal and (if present) primary fluid, are solved sequentially; for then, if the heat-transfer coefficients are high, the progress of the solution is akin to that of a five-mile

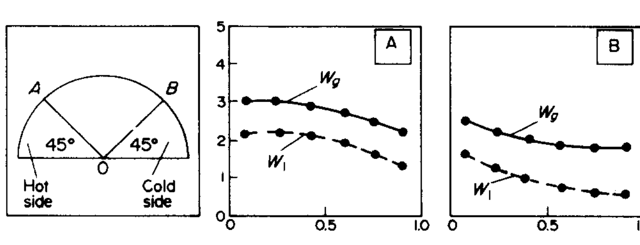

Figure 1. Axial velocity profiles at top of U-bend region in a steam generator (Singhal & Spalding 1979).

march with legs so tightly "hobbled" that each foot can move only an inch at a time. The better the heat transfer, the slower the solution.

3.2 *The solution*

The simplest way to treat the solid and the primary fluid is as "just another couple of phases"; for that is what they are; the nuclear-reactor problem is then a *three*-phase one; and the steam generator presents *four* phases for analysis. Provided that the theoretical framework is a general multiphase one, as is true of that presented in the Appendix, no difficulty presents itself.

Indeed, one is then struck by the simplifications: the "velocity distribution" of the primary fluid is easy to compute; for the fluid is constrained by the tubes and requires no analysis. The metal, moreover, does not move at all; so only conduction, time-dependent and phase-interaction terms appear in the finite-difference equation for the metal temperature.

The "hobbling" effect can be neatly avoided by the use of the "partial elimination algorithm" referred to by Spalding (1979). This eliminates, from the equation for the temperature of one phase at a point, the temperatures of all the other phases at that point (but replaces them by other-phase temperatures for *neighbouring* points). This is still not the best that can be done; but is is satisfactory for most purposes. At worst, it is as fast as a point-by-point (Gauss–Seidel) procedure; and usually it is much faster than this.

3.3 *Discussion*

From the mathematical and computational points of view, the thermally-active-structure problem has been adequately solved. However, it must once again be emphasized that the formulae which are perforce embodied in the computer code, in order to express the heat-transfer resistances between the various phases, are weak points in the models. It is there that research needs to be done, both experimental and, increasingly, by way of fine-scale applications of numerical models.

No results will be presented, mainly for lack of space; the URSULA code is in daily use, generating temperature distributions obtained in the above-described manner.

4. THE PRESENCE OF NARROW RESTRICTIONS, SLOWING CONVERGENCE

4.1 *The problem*

It is not widely recognised that the effectiveness of methods of solving finite-difference representations of partial differential equations depends very much on the degree of uniformity which the coefficients possess. Thus, the ADI (alternating-direction-implicit) method is widely recommended for solving heat-conduction problems; yet it will fail lamentably in some circumstances. For example, if heat is being conducted in a two-dimensional domain in which there are two insulating slots cut in the manner shown in figure 2, the rate of convergence will be very low.

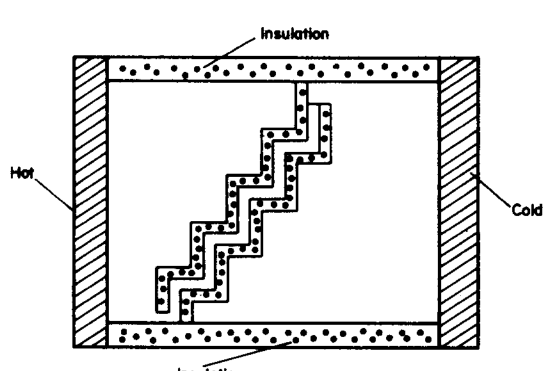

Figure 2. Illustration of a heat conduction problem for which the ADI method would converge only slowly.

There is no space to explain in detail *why* this is the case; but one way to put it is that the ADI method allows errors in the solution to "leak away" to regions of fixed temperature situated anywhere *along the lines of the grid*; so grid points which do not lie on such lines will lose their errors only slowly.

In general it may be said that convergence is slow whenever there are locations in the field connected to boundary-condition regions by highly restricted paths for heat and fluid flow.

Such restrictions are common in heat-exchange equipment. For example, baffles may be inserted so as to control the flow of shell-side fluid; and the external connection between the top and the bottom of the steam generator by way of the downcomer is a "restricted path" having a great influence on the behaviour of the equipment as a whole. Convergence is therefore slow under such circumstances when conventional methods of solving the equations are employed.

4.2 *The solution*

To render the heat-conduction problem of figure 2 easily soluble, all that is necessary is to insert into the equation-solving cycle one step in which the equations are solved, by the tri-diagonal matrix algorithm, for a string of grid points stretching from the hot to the cold boundaries *and passing through the restricted-flow region.*

Similar devices are needed when fluid flow is in question. For example, the domain accessible to the fluid is divided into "circuits" in such a way that every "restricted path" is traversed by one leg of the circuit. Then, at a stage in the computation at which mass and energy conservation prevails, the momentum equations are integrated around the circuits so that the pressure differentials (which should of course be zero) can be computed.

Next, small changes to the mass flows around each circuit are made, and the new pressure differentials are computed. From these, estimates are deducible of the further changes which will reduce the pressure differentials to zero; and these changes are then applied.

Because of the multiple non-linearities of the problem, it cannot be expected that the correct values of the mass flow rates will be achieved until many returns have been made to the main part of the solution procedure, where cell-wise adjustments of the dependent variables are carried out. However, iteration between the circuit and cell-wise adjustment procedures brings about convergence satisfactorily.

4.3 *Examples*

The circuit-adjustment procedure has been incorporated into the URSULA steam-generator code, and has achieved the desired effect of procuring rapid convergence. Table 1 contains typical results. It has also been employed successfully in many other codes produced by the author and his colleagues.

Table 1. Variation of downcomer flow rates with number of circuit adjustments

Adjustment number	Downcomer flow on hot side	Downcomer flow on cold side
0	1.500	1.500
1	1.639	0.7999
2	1.493	0.9605
3	1.524	0.9026
4	1.515	0.9101
5	1.515	0.9072
6	1.514	0.9074
7	1.514	0.9073
8	1.513	0.0074
9	1.513	0.9074

It should be mentioned that the circuit-adjustment procedure requires some physical and numerical insight for its optimum application; the choice of circuit path has to be made from almost countless possibilities; and some choices will be better than others. It will scarcely ever happen that a code will be devised with built-in circuit-choosing features; and efforts to introduce such features would be unwise, at the present time.

5. FITTING THE GRID TO THE EQUIPMENT OR COMPONENT GEOMETRY

5.1 *The problems*

(i) Before the flow in a reactor or a steam generator can be adequately predicted, the geometry of the equipment and its internal structure must be adequately described. This description includes, for example, the distributions of free-volume fraction and of heat-transfer surface throughout the space.

These distributions may exhibit discontinuities, for example at the top of the U-bend region in a steam generator; and baffles, support structures and distribution plates are always concentrated into small but important volumes. These discontinuities must be represented with sufficient realism.

(ii) In many reactors, and in some experimental steam generators, the premise of the first paragraph of section 2.1 is *not* true: the fuel rods or primary-fluid tubes are *few* in number (e.g. tens or hundreds rather than thousands and more).

This fact poses a problem: is it meaningful to "smear" the structural elements over cells when the numbers of elements and of cells are comparable in magnitude?

(iii) A third problem in this area is that the outer boundary of the integration domain may not coincide with the "natural" surfaces of a polar or Cartesian coordinate grid. The question arises of how to fit the grid to the prescribed geometry in an economical fashion.

5.2 *Solutions*

(i) For the first problem, there is little that can be done but to provide a sufficiently fine grid, and to be so careful and ingenious in the employment of computer storage and of arithmetical operations that the expense remains acceptable.

(ii) For the second problem, there are two solutions. The first is to adapt the grid to the structure in a one-to-one sense, as was done in the SABRE code for the prediction of flow in fast-breeder reactors (Gosman *et al.* 1973). Figure 3 illustrates the relationship between the grid nodes and the fuel rods in SABRE, for a cross-sectional plane. The grid remains Cartesian in its general features; but alternate links are missing, being interrupted by the presence of fuel rods. The locations of the axial-direction velocity nodes lie beneath the pressure nodes in the view shown.

Of course, the formulation of the momentum equations requires some care, because their directions are not orthogonal. However, once this has been done, a fairly realistic representation of the flow can be achieved.

(iii) A grid modification of a different type is needed to solve the third problem. Figure 4 shows what is needed in a steam generator having an enlargement of diameter near the top: the grid lines in vertical planes are bent so as to conform with the shell-diameter change; and the grid becomes thereby non-orthogonal.

In this case it is best to continue to work with axial, radial and circumferential velocity components. The non-orthogonality must therefore be taken account of by ensuring that the mass flow rates across cell surfaces which are conical, are appropriately affected by both the radial and the axial velocity components.

5.3 *Examples*

The techniques described above are all exemplified in the URSULA code, details of which have however not yet been published. Practice (iii), as has already been mentioned, is

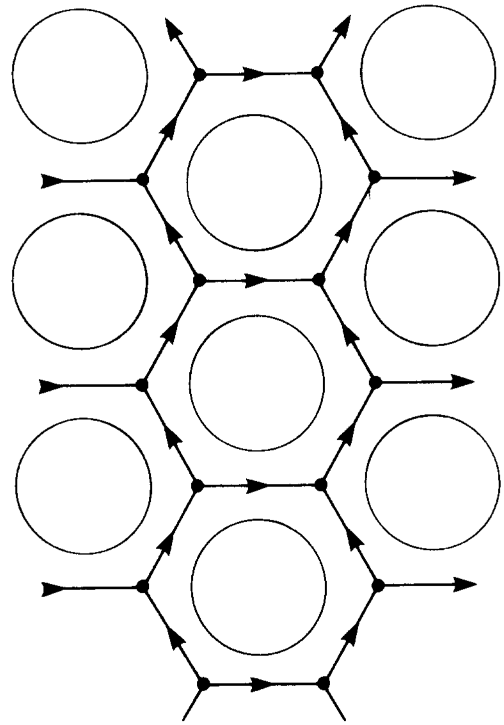

Figure 3. Arrangement of Grid Nodes for pressures (O's) and velocities (→ ↖ ↗'s), used in SABRE(13).

exemplified by Gosman *et al.* (1973); and the treatment of non-orthogonality can be found in papers by Abdelmeguid *et al.* (1978) in connection with flow around ships' hulls, and by Spalding (Nato 1979) in connection with flow in rod bundles.

6. GRAVITY STRATIFICATION IN 1-D AND 2-D MODELS

6.1 *The problem*

There are many two-phase flow situations in which the apparatus is elongated, or flattened; then it is common, and often permissible, to neglect variations in fluid properties in the "short" direction (or directions) and so to reduce the dimensionality of the mathematical problem. Examples are:

- A long pipe, in which variations normal to the axis are neglected.

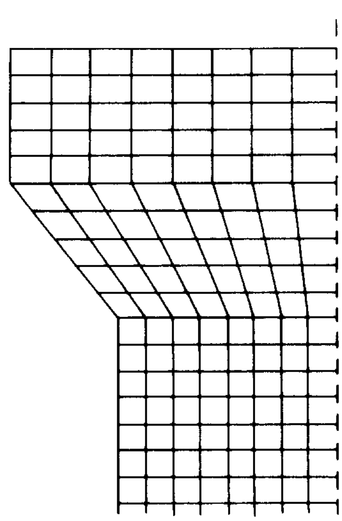

Figure 4. Arrangement of grid for the shell-diameter-enlargement region of a steam generator.

- A bundle of nuclear fuel rods, similarly treated as one-dimensional.
- The downcomer of a steam-generator, in which variations are considered only in the vertical and circumferential directions.

If there is a component of the gravitational field in the "short" direction, however, it may be that *stratification* of the fluids takes place. This occurs in a horizontal (or nearly horizontal) pipe when the flow velocity is not too large; and it must certainly be expected under some conditions in those nuclear reactors in which the rod bundles are arranged horizontally. Then although it may still be determined to disregard the variations in the "short" direction within a single phase, the fact that the ligher phase is at the top and the denser phase at the bottom *cannot* be neglected.

Gravity stratification introduces a new mechanism into the flow process: gradients in the interface between the phases produce additional forces on the fluids; and wave-propagation phenomena can be induced thereby.

Neglect of the gravity-wave phenomena can lead, in some circumstances, to radically incorrect predictions of, for example, the response of the two-phase flow in a pipe to changes in the boundary conditions.

6.2 *The solution*

Once the problem has been recognized, the solution is straightforward: the additional term is incorporated into the finite-difference equations; the links between the interface gradient, the pipe inclination, and the gradient in volume fraction are incorporated in as "implicit" a manner as possible; and the solution procedure is set in motion. The result is that the gravity-wave phenomena are predicted, with an accuracy which is as good as the realism of the reduced-dimensionality assumption permits.

6.3 *Discussion*

Baghdadi *et al.* (1979) are concerned with this problem, and present a few results permitting the influences of grid size and time step on accuracy to be determined. A further publication by Kurosaki & Spalding (1979) is in preparation. Unpublished work on the flow of compressed gas and condensate in under-ocean pipe-lines has demonstrated the feasibility of the solution procedure and the plausibility and practical interest of the results. Systematic comparison of predictions with especially-conducted experiments needs to be carried out.

Of course, the presumption that a pipe flow (for example) can be treated as one-dimensional, with or without gravity stratification, requires examination; and it will often be incorrect. Spalding (1979) examines this question, and indicates the possibility of constructing a model which, while appreciably more realistic than the one-dimensional ones, is very much less expensive than those based on application of the full three-dimensional system of equations. This is the FILIPA model, to be referred to again below.

7. THE PREDICTION OF THE FLOW REGIME

7.1 *The problem*

It has long been recognized that two-phase flows exhibit differences of flow regime that are sufficiently striking, visually, to warrant the introduction of special names; these include: "bubbly", "plug", "stratified", "wavy", "slug", "annular", "churn", "wispy" and others. An account can be found in the review by Hewitt (1978).

It is certainly to be expected that the rates of heat, mass and momentum transfer obey different quantitative laws according to which regime prevails, whether the transfer in question is from one fluid phase to the other, or between a fluid phase and the walls of the duct through which it flows. Therefore, several workers have attempted, after examination of experimental observations, to connect the occurrence of each flow regime with combinations of supposedly characteristic quantities, for example the average "quality" of the flowing mixture, the mass flow rates, etc. Flow-pattern maps, of the kind proposed by Baker (1954) for flow in horizontal pipes and by Hewitt & Roberts (1969) for flow in vertical pipes, represent attempts to systematise this knowledge, such as it is.

In equipment and components of the kind discussed in the present paper, the need for knowledge of the flow regime is no less than for flow in pipes; but the amount of that knowledge which currently exists is even scantier. For practical purposes, it needs to be recognized, there is *no* reliable knowledge about what flow regimes will come into being under the conditions of engineering operation; still less is there quantitative information about the associated friction and heat-transfer laws.

7.2 *The solutions*

Faced with this problem, one can do one of three things, apart from either giving up the attempt to model equipment flows at one extreme, or, at the other, naively believing whatever comes out of the computer. These are:

(i) To be content with order-of magnitude and limiting-case predictions.

(ii) To institute a systematic experimental study for conditions of interest.

(iii) To initiate a numerical-modelling study in which, because it is the multi-phase flow within individual sub-channels that is being modelled, there is a fair prospect that the mechanics of the process can be realistically represented.

Method (i) is the only one that can be followed immediately; and it behoves the creators of codes such as URSULA constantly and loudly to caution potential users against beliving that, because a particular "flow-regime map" has been incorporated in the code in response to a specific request, any reliance should be placed upon its realism at all. Properly handled, limiting-case studies, in which doubtful parameters are given systematically their largest and smallest credibile values, can give extremely valuable (and *valid*) information; it is the predictions based upon the complex and doubtfully applicable formulae, extracted from the literature uncritically, which do the damage.

Concerning method (ii), it is necessary to remark that it is of course necessary; but excessive hopes should not be entertained of its early issue in success. The low yield of experiments on pipe flow must be recognised; and, there are many observations which demonstrate that the whole concept of a "flow map" is based on an invalid hypothesis: in practice, there is a very strong "history effect" of upstream conditions on the flow regime; *local* flow rates, etc. do *not* determine the regime.

That being so, it is to method (iii) that the ambitious researcher may well look; for, though the difficulties are not to be taken lightly, there *is* a chance that a detailed application of numerical modelling at the sub-channel level can provide a quantitative indication of what multiphase flow regime will result from given local *and* upstream conditions; for three-dimensional transient analyses can certainly handle the "history effect".

It is not necessary, at first, to employ a full-3-D analysis. Much insight can be gained by at first considering the FILIPA model (Spalding 1979), comprising a one-dimensional vapour phase, a one-dimensional droplet phase, and a two-dimensional film phase. This need not be expensive to operate, and it will certainly set limits to the conditions in which the different regimes can exist.

7.3 *Discussions*

Limiting-case studies have been conducted on one-dimensional representations of steam generators using the PLANT code (as used by Baghdadi *et al.* 1979 and Kurosaki & Spalding 1979); further studies are being conducted with URSULA. Some of these have been published elsewhere (Singhal & Spalding 1979).

Concerning progress along the lines of method (ii) it will be for others to report.

Of method (iii), namely the numerical-modelling approach, it is worth reflecting upon the large amount of research funding now being devoted to the numerical computation of very simple turbulent flows (see for example work by Chapman 1979) and comparing it with the fact that none whatsoever is (to the author's knowledge) being expended on multiphase flows at the proposed level. Here is a technical objective, that of producing a flow-regime predictor, that the multiphase-flow community could very reasonable set for itself; the decision to do so would be a memorable outcome of the present meeting.

8. CONCLUDING REMARKS

Although space limitations have prevented sufficient exemplifications of all the assertions and recommendations which have been made, so that the sceptical reader may reasonably await further proof, it is hoped that at least some credence has been gained for the paper's main argument which, in summary, is that:

- The mathematical difficulties of solving the differential equations of multiphase flow have been surmounted.
- The economy of the methods of solution is such that it is now practicable to solve problems of three-dimensional two-phase flow with unequal velocities.
- Special features distinguish the modelling of flows in equipment items and their components; and all but one of the associated problems have been overcome.
- The major need is for some way of predicting the flow regimes which are likely to occur.
- The most hopeful method of solving the flow-regime-prediction problem is by fine-scale application of numerical modelling.

Despite formidable remaining difficulties, the prospect for increased successful modelling of multiphase flow phenomena appears to be very bright.

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