ENHANCED VISUALISATION OF COMPLEX THERMOFLUID DATA: VERTICAL AND HORIZONTAL COMBINED CONVECTION AND MICROSCALE HEAT TRANSFER CASES

MA Atherton[1], MW Collins[1], S Piva[2] and GS Barozzi[3]

[1] School of Engineering Systems & Design, South Bank University, London SE1 0AA, UK
[2] Dipartimento di Ingegneria, Universita di Ferrara, 44100 Ferrara
[3] Dipartimento di Scienze dell'Ingegneria, Universita di Modena, 41100 Modena

ABSTRACT

In general, convective heat transfer is an 'n-dimensional' problem where n is well in excess of 3 for steady flows. Traditionally, the method of dimensional analysis results in a small number of dimensionless groups. In the case of steady forced convection these can reduce to three, namely the Nusselt (*Nu*), Reynolds (*Re*) and Prandtl (*Pr*) numbers, for heat transfer, fluid flow regime and fluid properties respectively. Again, traditionally, data are presented on log-log graphs, say of *Nu* versus *Re*, with *Pr* being a possible third parameter. For natural convection, the Grashof number (*Gr*) expresses buoyancy effects in place of *Re*, while for combined (natural and forced) convection *Gr* becomes additional to, rather than replacing, *Re*.

Using sets of data for:
(a) vertical combined convection in nuclear safety,
(b) horizontal combined convection review material, and
(c) microchannel heat transfer,
in the first part of this paper we survey this problem.

We reach the following conclusions: that heat transfer data are presented in either 'holistic' or 'reductive' modes, and that other thermodynamic performance data are related to the generic scientific cases of (a) 3-dimensional space and (b) multi-dimensional space. In the second part of the paper we present a first attempt at applying design-type procedures to specifying this problem. Visualisation priorities are suggested from which particular solutions will be developed in future.

1. INTRODUCTION

Convective heat transfer is a most important subject from two main causes. Firstly, as giving quantitative performance data (and very often in conjunction with matching friction factor, or pressure drop performance) it becomes the essential scientific basis of almost limitless items of engineering equipment, such as heat exchangers. With the progressively smaller scales of computer microprocessor 'chips' and their cooling requirements and other applications, the major field of microscale heat transfer has emerged. No doubt this will be followed by nanoscale transport processes in the course of time.

Secondly, convective heat transfer is significant because of its complexity. Since the heat transfer is affected by so many variables, it is both demanding, and usually fascinating, to understand - the 'Discussion of Results' sections of so many research papers are proof enough of this.

Until comparatively recently, 'research and development' in convection for engineering has followed the same approach. Genuine theoretical work was limited to standard cases of laminar flow, and there was no procedure to treat the three-dimensionality and turbulence of so much of the underlying fluid dynamics. Hence, using the (quite correct) rationale of thermal similarity and dimensionless groups, empirical methods were used - experiments being costly, slow and somewhat limited in overall data. Local heat transfer was obtained via invasive thermocouples.

As a consequence the presentation of data has remained virtually unchanged for decades. For example, engineering textbooks such as Rogers and Mayhew [1] retain consistency of treatment in this regard.

The present situation could hardly be more different from the past, although it must be acknowledged that the traditional approaches are still used and are valid. However, in analysis Computational Fluid dynamics (CFD) and heat transfer, with appropriate turbulence models can treat even three-dimensional unsteady problems. Somewhat simpler cases are readily 'PC treatable'. In experiment, a range of non-invasive, optically oriented whole-field methods have become available, thus matching the computational approaches.

We therefore ask ourselves the question - Are the current methods of presentation adequate, and if not, how could they be improved? Ultimately the data are used to characterise performance, and in this context, presentation would involve multi-dimensional space. This then becomes part of a generic scientific problem, as the 'multi-dimensional space' concept appears in a number of fields.

In this paper, we will take heat transfer presentation data especially from the areas of vertical combined convection (nuclear safety and performance), horizontal combined convection, and microscale heat transfer. Consideration of these, leads to the introduction of a radical 'top-down' formal design procedure, on the basis that in the broadest sense this subject area may be considered as engineering design. In this regard, and so in specific design terms, it is important to clarify the requirements of the user, i.e. in terms of who they are and what they need. The needs of two groups of users are distinct: the designer who is looking for practical information to use in the solution of a design problem; and the engineering specialist seeking a better understanding of the phenomena presented. A positive outcome will be user-friendly to both. Also in both cases it is anticipated that it will be important to visualise heat transfer and pressure drop, normally represented by *Nu* and friction factor respectively. A list of priorities to be met will emerge that could include clear indication of the significance (in combined convection) of forced convection only and wall conduction in particular zones of the visualisation. We envisage, prima facie, that the 2D graph will be extended to 3D with perhaps more dimensions addressed through layering and sequential plots. The latter reflects the continued preference generally for visualisation in the printed medium. This represents a first attempt to treat the visualisation problem in such a manner.

2. VERTICAL COMBINED CONVECTION

In the early 1960's extensive experimental work was carried out to determine thermal performance data for Magnox reactors under a range of postulated fault conditions. This was to demonstrate reactor safety, using 'best practice' procedures of that period (Collins and Whaley [2]).

Estimates of coolant mass flow rate under various fault conditions, ranged from zero to reactor standard operating levels. The former and latter extremes, were therefore 'natural convection' and 'forced convection' (natural effects ignored) respectively, with the intervening range represented as 'vertical combined convection'.

The test loop involved simulating a reactor vertical channel, using six full-scale fuel element Magnox 'cans', the nuclear heating being simulated by internal thin-wall electrical resistance heating. Each Magnox 'can' and wall 'liner' was extensively thermocoupled in a sophisticated manner developed over hundreds of hours of test work.

Basic test data were, therefore, temperatures (Fig. 1a) for a typical radiation heat transfer (elimination) test from which minimum and average heat transfer were obtained (Fig. 1b) for an adapted Stanton number - Reynolds number relationship, $?_1$ and $?_2$ being non-dimensional thermal property functions. The convective heat transfer was maximised by a four-quadrant swirling flow arrangement engendered by 'multi-start' finning. Minimum heat transfer was at least as important as average heat transfer, as it indicated a maximum temperature (hotspot) for purposes of Magnox stability limitations.

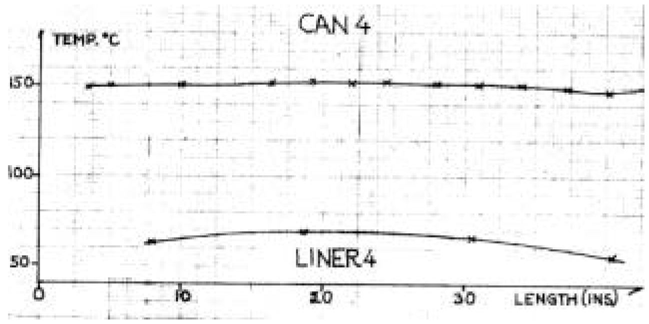

Figure 1a Magnox can & liner axial temperature distribution (Fig. 7 in [2]).

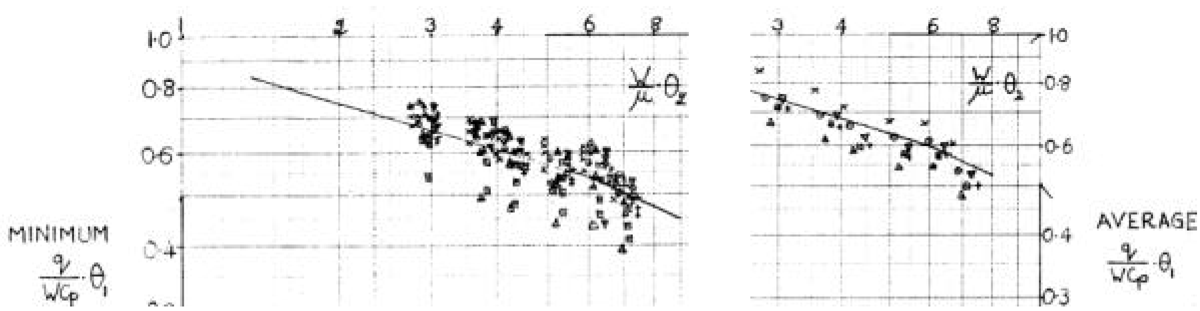

Figure 1b Minimum and average heat transfer for vertical rig (Fig. 9 in [2]).

The complete heat transfer data were correlated as in Fig. 2, a log-log plot, which collapsed the entire performance to within ±40%.

In conventional dimensionless group notation, this could be represented as:

$$Nu = a\left\{\left[Ru + b\sqrt{Gr}\right]Pr^{c}K^{d}\left[1+e\left(D/L\right)\right]\right\}^{f} \qquad (1)$$

where K is the gas/metal thermal conductivity ratio,

D/L is the effective diameter/length ratio

and a-f are empirical constants.

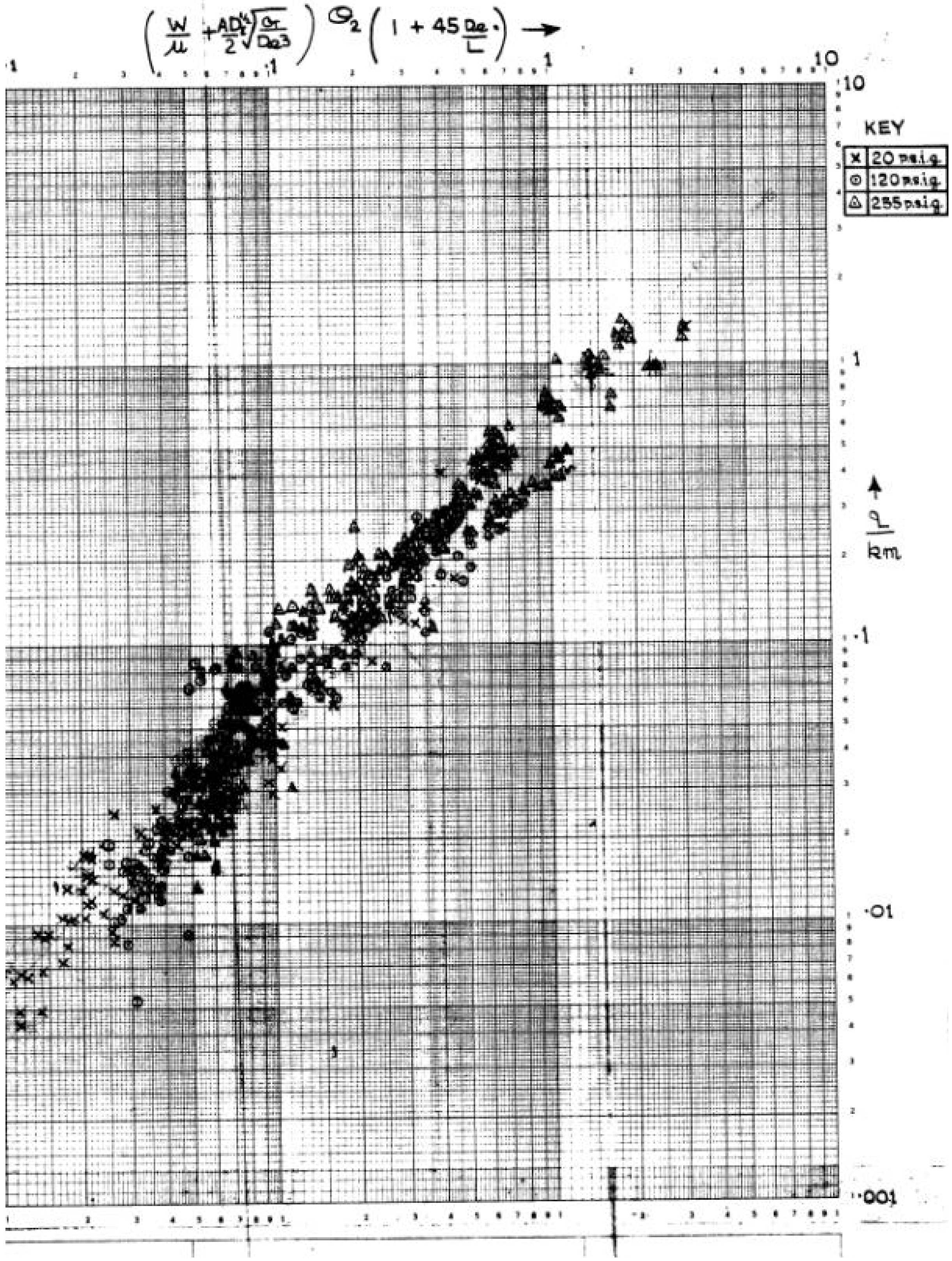

Figure 2. Correlated heat transfer data for helical fuel element (Fig. 22 in [2]).

More generically:

$$Nu = function\left\{Re, Gr, Pr, K, {L}/{D}\right\} \text{ (vertical)} \quad (2)$$

For purposes of this paper, Fig. 2 may be termed a holistic relationship, that is, it gives an overall representation of the data for performance purposes. The basic or reductive data are represented by many graphs like Fig. 1b, or more purely by a very large number of data sets like Fig. 1a.

Matching friction factor data (for pressure drop performance) are not considered here for reasons of space. This nuclear safety work was the catalyst for the finite difference modelling of vertical combined convection ([3], [4]), but space again does not allow more consideration.

3. HORIZONTAL COMBINED CONVECTION

The problem of horizontal combined convection is substantially more complex than that of the vertical case. This is because the gravitational force field is at right angles to the forced flow rather than being in line with it. Hence it means that a two-dimensional model (assuming circumferential symmetry for a tube, say) is quite inadequate for the horizontal case, whereas it is quite suitable for the vertical case.

Because of this complexity, it is a matter of considerable interest to know when horizontal convection can be regarded as truly forced, that is when the natural convection can be ignored. Allen et al [5] (and see subsequent written discussion) undertook such a study. Alternative criteria correlations, reproduced here as Fig. 3, were given as 500 (for *Gr*z/Re*, where *z* is the axial co-ordinate) or 2 (for $(Gr^*Pr)^{1/4}/Nu$).

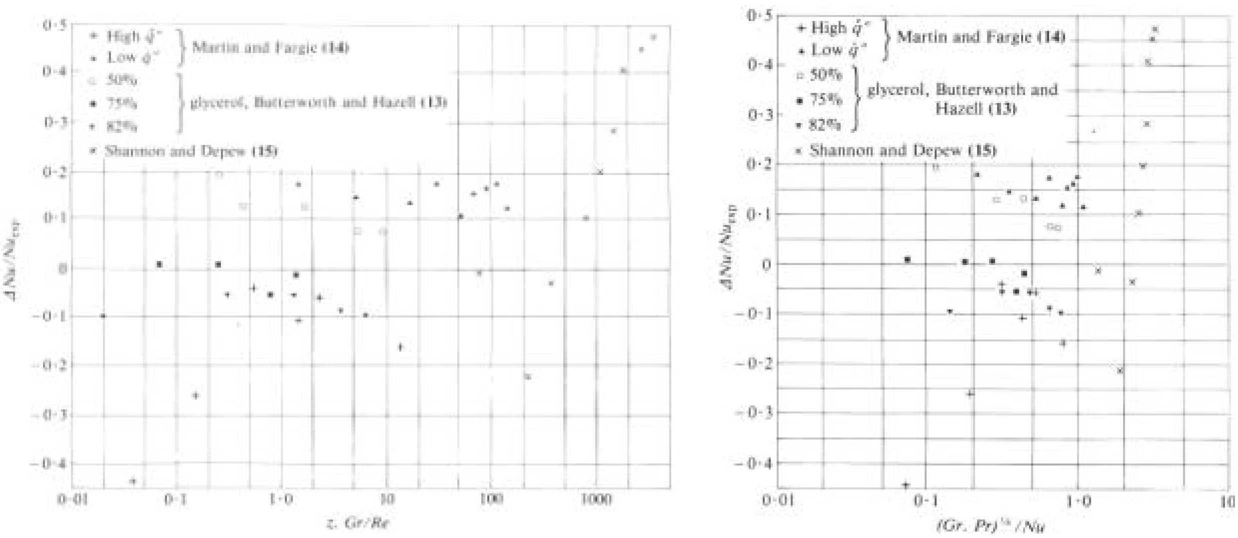

Figure 3. Suggested correlation using different dimensional groups for abscissa from [5].

The thesis study of Barozzi [6], with associated papers, cannot be considered here, but it eventually resulted in the current publication of a substantial and detailed review (Piva et al [7]). This is to be followed by a more focused review of part of the problem, namely for circular tubes with constant heat flux (Piva et al [8]). In fact it was the review [7] that provided the motive for a radical re-think of the issue of visualisation of data.

Despite the length and closely written character of the review – actually an expansion of a previous UIT conference paper [9] – it proved impossible to use meaningful graphical material. Instead the publications were summarised in the form of extensive series of Tables.

One performance aspect of interest (to be covered in [8]) is the question of the relationship between an assumed fully developed *Nu*, and the alternative (to *Gr*) convection dimensionless group, *Ra* (the Rayleigh number). Various analytical solutions have been produced for this relationship, and these have been systematised (for consistent definition) and compared in Fig. 4. Each relationship is for a fixed *Pr*, but *Pr* varies from 0.72 (for air) to 8 .

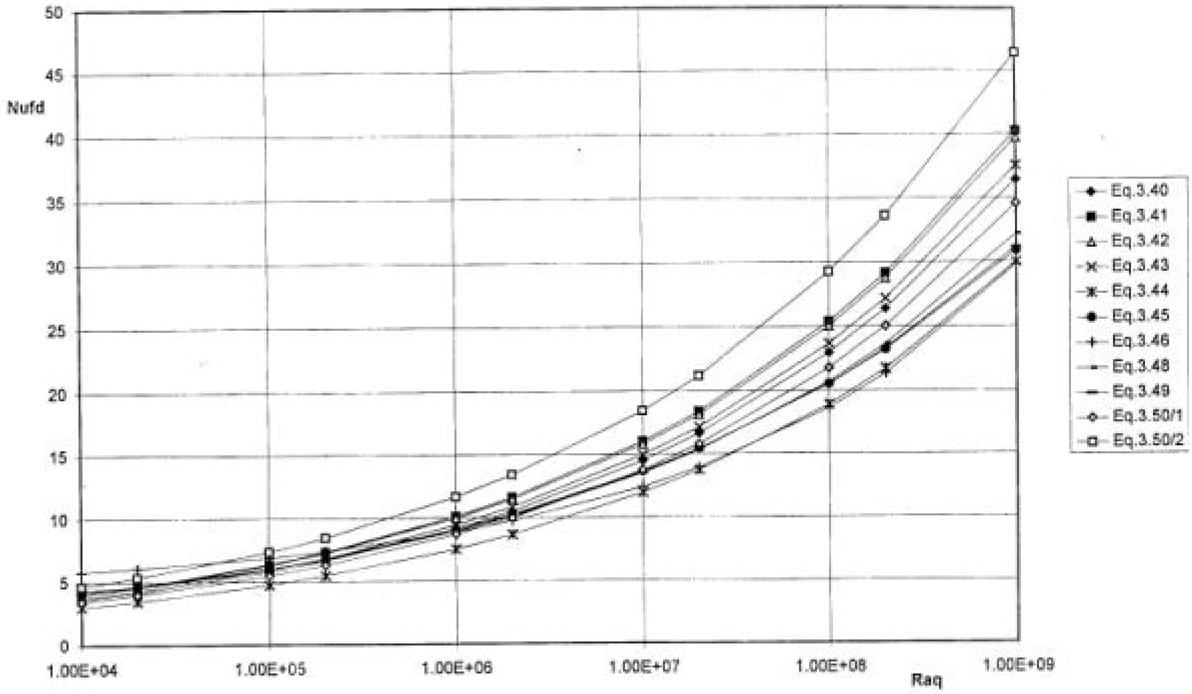

Figure 4. Nu versus Ra under various values of Pr for convection in horizontal flows from [8].

It is evident from the number of relationships in Fig. 4 that horizontal combined convection is an important field of study. In dimensionless group terms:

$$Nu(\text{fully developed}) = function\{Ra, Pr\} \qquad (3)$$

Generalising, by allowing for Re effects, axial length effects on local Nu, and wall conduction (related to the *K* of equation (2)) we have:

$$Nu = function\{Re, Gr, Pr, K, L/D\} \text{ (horizontal)} \qquad (4)$$

as for the vertical combined convection of equation (2).

4. MICROCHANNEL HEAT TRANSFER

With the miniaturisation of devices in general, and the consistently reducing scales of computers in particular, microchannel heat transfer has become a key field of study. Manufacturing considerations have caused the ‘rectangular channel’ to be the standard geometry, and this is a prima facie extension of the series of studies by Morini and Spiga (for example [10, [11]) on rectangular channel heat transfer for conventional dimensions. In fact, combining the rationales of this series [12] with the complementary work by Collins [13] on viscous dissipation/viscosity variation, we (Morini and Collins) are initiating a numerical modelling approach using a Computational Fluid Dynamics code. Unlike circular tubes, rectangular channels have [10] eight alternative heating modes, depending on which of the four walls has/have a heat input. Many of the results of Morini and Spiga are presented in a three-dimensional manner (for each of the various modes) and a typical output is shown as Fig. 5. (Temperature is used as a base parameter as in Fig. 1a).

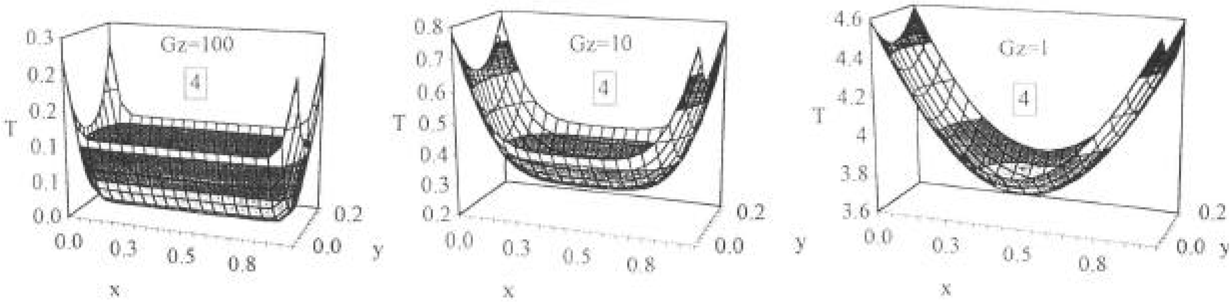

Figure 5. Temperature distribution in the thermal entrance length, four heated walls from [10].

The predominant research in microchannel heat transfer is experimental (for example, the work of Wang and Peng [14]). The base data are heat transfer coefficients for an example (for the 3rd of a set of 6 machined rectangular microchannels in a block) being shown as Fig. 6.

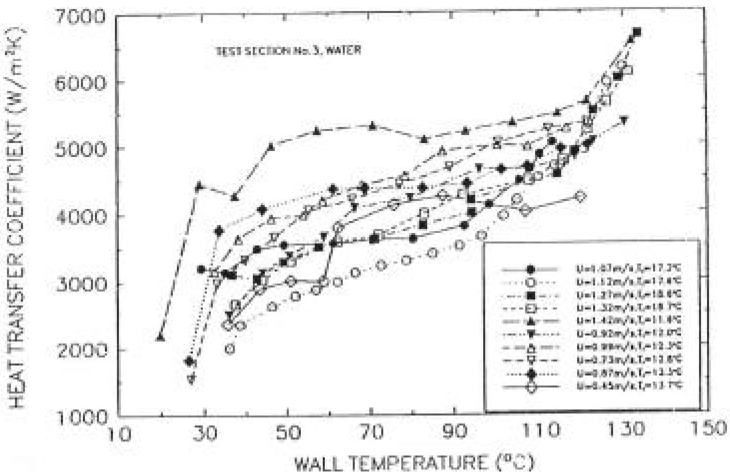

Figure 6. Variation of heat transfer coefficient with wall temperature from [14].

When it came to dimensionless groups, however, as *Nu-Re* correlation (*Pr* being defined for the single liquid methanol) could not correlate laminar-transition-turbulent regions (Fig. 7), and it was recognised that unusual effects were occurring for laminar flow. For turbulent flow, the constant in the normal *Nu, Re, Pr* correlation was reduced by a factor of about 4, indicating full turbulence being initiated at *Re* = 1000-1500 instead of 2300.

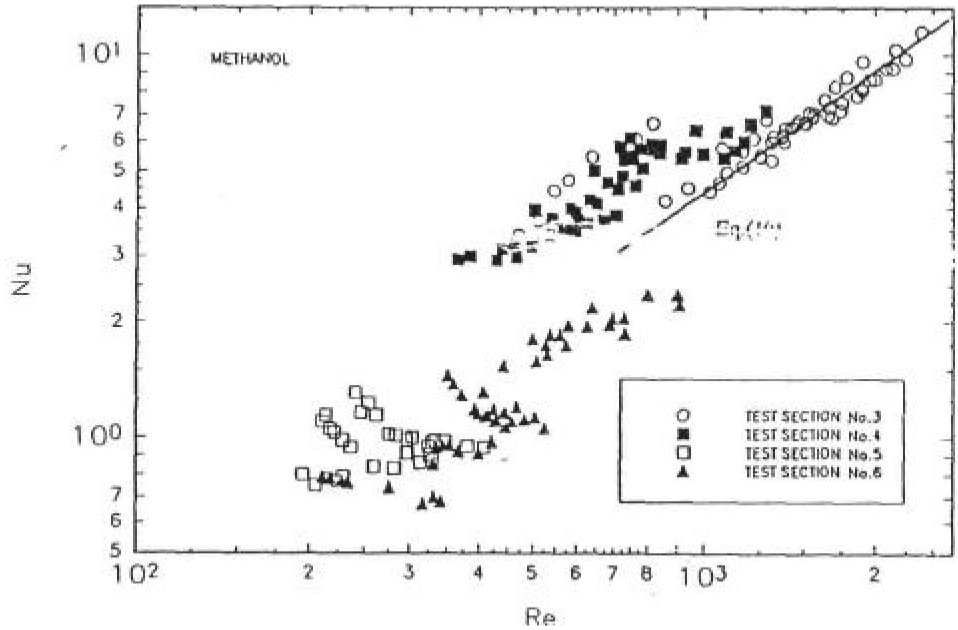

Figure 7. Nusselt number versus Reynolds number for methanol from [14].

The data of Wang and Peng were recorrelated subsequently by the introduction of *Br* (Brinkman number) as a parameter (see Fig. 1, Ref. [15]) shown in Fig.8 (Fig. 5 of Ref. [16]) by Tso and Mahulikar.

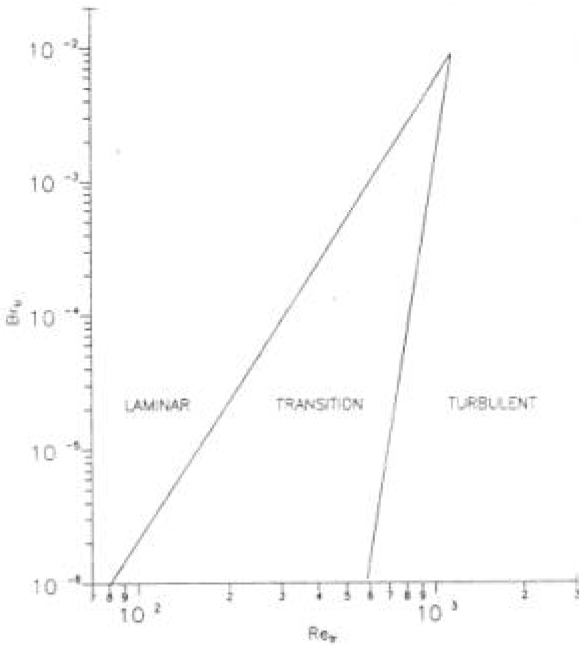

Figure 8. Combined laminar-to-transition and transition-to-turbulent loci from [16].

Hence, the microchannel transition data, are no longer a line, one a two-dimensional graph, but a surface on a three-dimensional graph, (*Nu-Re-Br*), or, more generally, a surface on a multi-dimensional graph.

5. SURFACES IN THREE-DIMENSIONAL SPACE

Surfaces in three-dimensional space are the maximum we can display, and, as with Fig. 7, here, are used in thermal contexts, in familiar form Fig. 9 (Pressure, Volume and Temperature) from [1] and in unfamiliar form Fig. 10 from [17]. The latter, in fact being a depiction of energy density and information density as functions of time, is, like Fig. 9, a thermodynamic graph since information density stems from the Second Law of Thermodynamics.

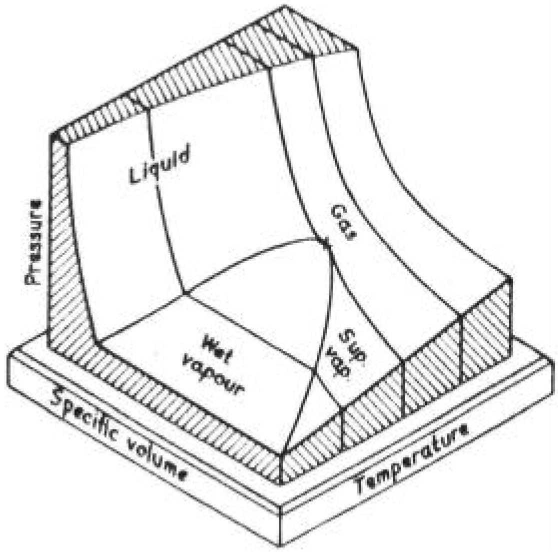

Figure 9. p-v-T surface from [1]

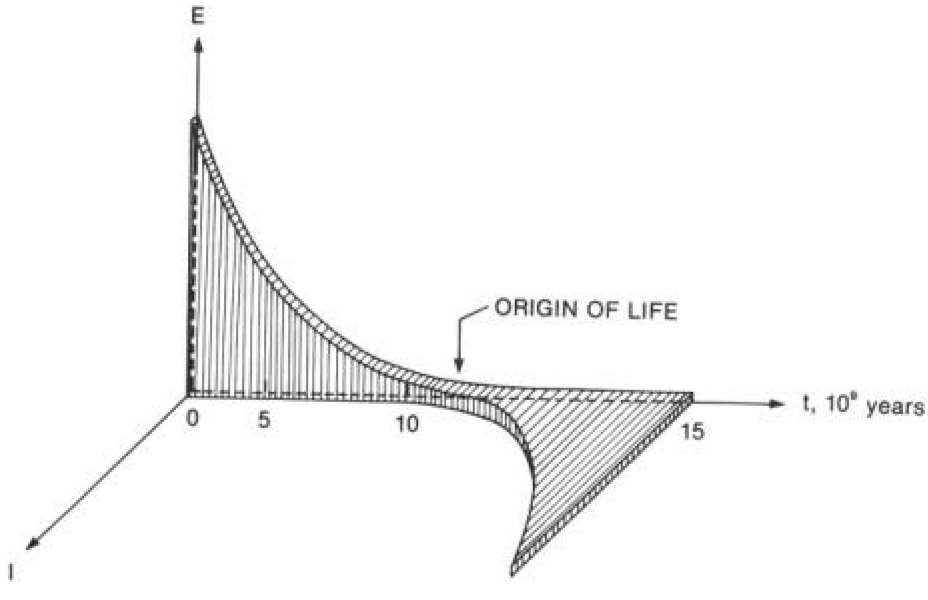

Figure 10. Energy density and information density as functions of time from [17].

6. SURFACES IN MULTI-DIMENSIONAL SPACE

While, strictly, these cannot be displayed, we can appreciate that (for microchannel heat transfer, say) the $Nu = f(Re, Br)$ surface deducible from Fig. 7 and Fig. 8, could be generalised (including natural convection):

$$Nu = f\left(Re, Gr, Br, Pr, ...\right) \tag{5}$$

In fact, in heat transfer performance, multi-dimensional space is used perhaps more than we realise, and for an old example we return to the nuclear industry. Lewis [18] shows how the operating and optimised design of Magnox power stations was achieved by analysing (using early digital computers) the cost of a 30-parameter system. In fact the system as used was a simplification of the more basic 100-parameter system. Two aspects of the cost are fairly obvious, namely, 'capital cost' and 'generating cost per annum', and Fig. 11a and Fig. 11b show how these are affected by the fundamental parameters of Reactor Gas Inlet Temperature, and Steel Pressure Vessel Plate Thickness.

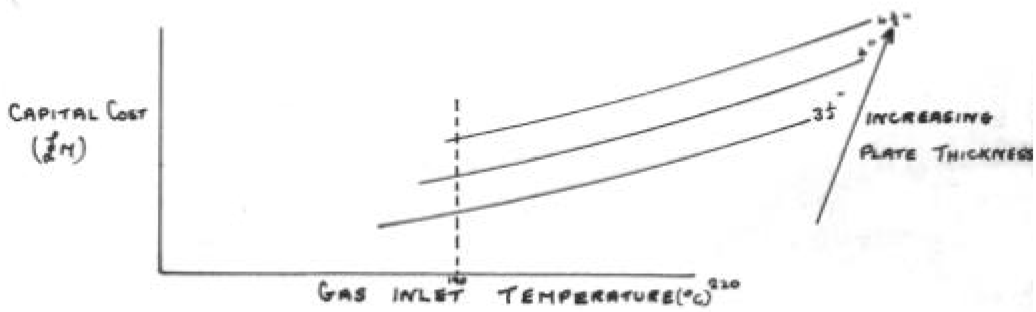

Figure 11a. Variation of capital cost with reactor inlet temp and plate thickness from [18].

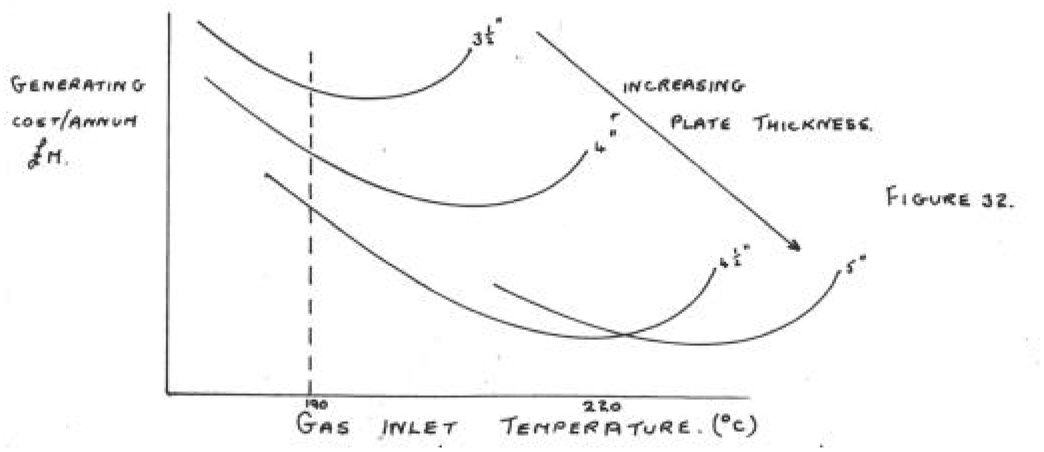

Figure 11b. Effect of inlet temp and plate thickness on generating cost from [18].

Because nuclear power stations are capital intensive, but of lower running costs, what is basically an economic reconciliation may be made by incorporating the capital cost in the generating cost. At the time this was known as the Weighted Generating Cost Function, G*.

While (unfortunately for our purposes) no illustration is available for this, the ‘tracing’ of an optimisation exercise was similar to the tracing of contours up a slope (‘hill-climbing’), where the ‘height’ corresponded to a kind of ‘inverse G*’.

Surfaces in multi-dimensional space form a common feature of scientific situations, and an example is given from biology. Fig. 12 is an explanation-type diagram of life-cycle shape changes in organisms [19]. Development from egg-to-embryo-to-adult is represented by a series of downward trajectories, the cycle being completed by egg formation from the adult. Hence the vertical axis represents time, and areas (horizontal) represent varieties of shapes.

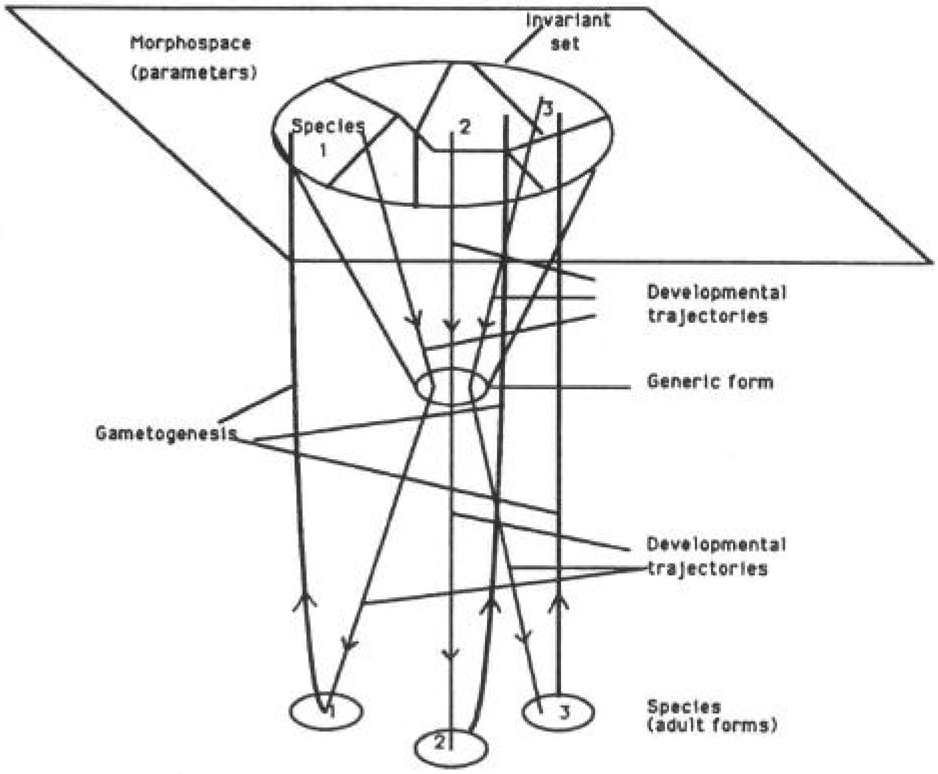

Figure 12. Relationships between morphospace, invariant sets, morphogenetic trajectories, generic forms, and species life cycles from [19].

7. VISUALISATION PROBLEM

The old sequence of quantitative data transfer via log-log plots was always laborious, often inaccurate, and is no longer necessary. In any case, with the possibility of computer generation of graphics, at least three-dimensional surfaces could be used to aid understanding, as in the discussion of microchannel heat transfer.

While we have considered only heat transfer performance-type data, there is the allied problem of how to exploit by way of visualisation the enormous quantities of three-dimensional field data. These could be produced by way of optical measurement methods, or by computational predictive means.

Rather than propose ad hoc improvements, the rationale of our approach is to apply formal design procedures, and through them visualisation methods. Of course, we anticipate that the use of dimensionless groups will continue, since they reduce the number of variables.

8. DEVELOPING A VISUALISATION SPECIFICATION

Before a means of visualising the data can be determined, it is important to clarify the requirements of the expected users (identified in the introduction) in general and specific terms. In general terms, we have identified three overall requirement groups, namely (left most column in Table 1):

(a) Provide insight into <u>system performance</u>.

(b) Highlight the nature of the <u>data structure</u>.

(c) The <u>ease of use</u> in obtaining both of the above aspects.

At this early stage it is most convenient to gauge the relative importance of each group to the user and this is reflected in Table 1 by the distributing 100 percentage points to system performance, data structure and ease of use as 30%, 50% and 20% respectively. Capturing more specific detail on what the user desires from the ideal (but for now unknown) visualisation technique is essential before we attempt to define the 'solution space'. This detail is shown in Table 1 as 'User Requirements' and is intentionally expressed in terms that are judged to relate to what is required from the visualisation. The importance of the User Requirements (UR) within each group have been assessed and represented as scores whose sum is equal to the percentage importance of the group so as to maintain the general balance independent of the number of specific expressions.

	% imp	***User Requirements (UR)***	**imp** \ ***Visualisation Specification (VS)***	*find operating points*	*read parameter values*	*show characteristic behaviour*	*highlight influence of important parameters*	*indicate maxima/minima performance trends*	*show temperatures at which values are calculated*	*indicate experimental uncertainty*	*produce groups, zones or surfaces of ...?*	*avoid log-log scales*	*show when forced convection is not relevant*	*show conditions under which buoyancy is insignificant*	*show when wall conduction is insignificant*
sys perf	30	*looking for practical design information*	**10**	*9*	*3*	*9*	*9*	*9*					*9*	*9*	*9*
		understand phenomena	**8**			*9*	*9*			*3*					
		identify where optimal design exists	**12**	*9*	*1*			*9*							
data structure	50	*clarify the role of individual parameters*	**15**			*3*	*9*	*3*							
		show limits of operating space	**17**					*3*			*3*		*3*	*3*	*3*
		indicate where instability begins	**10**	*1*		*3*		*9*		*1*					
		indicate quality of the data	**8**						*9*	*9*					
ease of use	20	*easy to read*	**20**									*9*			
			priority scores:	*208*	*42*	*237*	*297*	*384*	*72*	*106*	*51*	*180*	*141*	*141*	*141*
			priority ranking:	***4***	*12*	***3***	***2***	***1***	*10*	*9*	*11*	***5***	*6*	*6*	*6*

Table 1. Visualisation Planning Chart

Having expressed *what* is required of the visualisation it is then necessary to translate this into *how* the ideal visualisation technique should address it. The statements termed the Visualisation Specification in Table 1 aim to specify the problem in technical terms that will aid an imaginary visualisation expert in identifying the most appropriate solution. To this end we feel that it is important that the Visualisation Specification (VS) is expressed as 'solution-neutral' verb-noun couplets, as shown – that is, to provide concise and meaningful descriptions avoiding terms that suggest a particular solution if possible. This will keep the specification open to the maximum number of viable solutions as possible and thus an ideal solution is more likely to lie within the boundaries.

The many-to-many relationships between the UR and VS have been judged on a 9-3-1 scale representing dominant, strong and significant relationships respectively. A priority score for each element of the VS results from the column-wise sum of the products of these relationship matrix values and the relevant importance values.

For clarity these scores are simplified as a priority ranking, which provides a clear agenda for designing the most appropriate visualisation solution.

The approach described above is a simplification of the Quality Function Deployment (QFD) method that has been extensively used in industry for the design of products and services [20]. Another advantage of this approach is that it promotes a consensus amongst those involved in designing a solution to a problem.

9. DISCUSSION

In completing Table 1 the authors are aware of the limitations of relying on estimating the User Requirements in place of an extensive user survey. Thus in this first attempt there may well be specific needs not represented correctly. In particular, 'ease of use' warrants expansion beyond 'easy to read' at least in aesthetic terms in order to create a greater sense of the Visualisation Specification having addressed this general issue. As it is, the influence of this UR group on the design process is limited to a single aspect of the VS.

The specific terms of the VS identified would also benefit from more detailed consideration in order to be satisfied that all possible dimensions of the problem have been addressed. However, by virtue of the relationships assessed, the highest priorities for the VS are namely:

(i) Indicate maxima/minima performance trends.
(ii) Highlight the influence of important parameters.
(iii) Show characteristic behaviour.
(iv) Find operating points.
(v) Avoid log-log scales.

The score for the first priority indicates that showing maxima/minima performance trends is of overwhelming importance in order to satisfy the user. The fifth priority, avoiding log-log scales is not particularly well defined in solution-neutral terms and should perhaps be reworded. But at least the need to consider alternatives to log-log scales is highlighted.

The above are design-related but these priorities can be reinterpreted in heat transfer terms:

Priority (i) represents the engineering significance of the data (in our case $(q/wC_p)?_1$ or *Nu*) which include a clear statement of uncertainty.

Priority (ii) represents the basic understanding using such graphs as *Nu-Re* and *Nu-Ra* plots. However, in the references used there is a general lack of information on the influence of 'fluid properties' and geometrical variations. Also 3-dimensional surface representation, say *Nu-Re-Gr* is almost totally absent.

Priority (iii) indicates the necessity for understanding shapes of relationships, usually currently done on a reductive basis, say *Nu* versus *Re* is 'convex' or 'exponential'.

Priority (iv) harks back to (i). Where, on the graphs presented in a paper, is the likely operating point, or range of points used in practice? It could be that the uncertainty in the data for such a range is different from the average value.

Finally, priority (v) indicates the difficulty of accurately reading from this conventional presentation. In fact, if the log-log approach is considered desirable in the context of other priorities not considered here, it could be that the basic data should be stored and recoverable over the internet.

Thus Table 1 is a Visualisation Planning Chart providing a means of visualisation giving both practical design information and better understanding of the phenomena. We are mindful that addressing one or the other independently could be reflected in the User Requirements to be listed as well as the importance scoring, which would inevitable lead to different visualisation priorities.

CONCLUSIONS

The presentation of data for complex heat transfer regimes has hardly changed over recent decades, despite the availability of whole-field measurement methods and use of CFD-type prediction approaches. In this paper, we have attempted to demonstrate the range of visualisation graphs currently used, and the problems involved in studying the new field of microscale heat transfer. Rather than simply adapt current usage, we have applied formal design procedures to give a 'top-down' approach in defining the visualisation specification, stopping short of proposing solutions at this stage. This is a 'first attempt', and we would welcome reactions and contributions in assessing its value and/or developing it further.

ACKNOWLEDGEMENTS

We are grateful to G L Morini for helpful discussions on microchannel heat transfer.

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