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TEACHING HEAT TRANSFER AND FLUID FLOW BY MEANS OF COMPUTATIONAL FLUID DYNAMICS (CFD)

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ABSTRACT

What

Traditional teaching of heat transfer and fluid flow relies heavily on the student's abilities (a) to perform certain mathematical operations, and (b) to comprehend their consequences in physical terms. The mathematical operations are of the '**functional-analysis'** kind, involving differential equations, the solutions of which can be expressed in terms of commonly-used functions: trigonometric, hyperbolic, error, Bessel *etc.*

The lecturer argues that modern-times teachers should reduce the emphasis on **functional** analysis and exploit the greater power of **numerical** analysis.

Why

Traditional teaching methods have limited success for two disparate reasons:

(1) they cannot reach students who, although possessing other abilities more-often required by practising engineers, are weak in respect of one or other of abilities (a) and (b) above:

(2) the methods can handle only idealised physical situations, of simplified geometry, material properties and flow-defining conditions, which are seldom encountered in engineering practice.

After graduation, engineers perforce make use of numerical analysis to perform their professional tasks of equipment and process design; and they would do so with more success if, as students, they had learned the merits, **and the drawbacks,** of computational fluid dynamics.

Practising engineers in fact make scant use of the abilities (a) and (b), weakness in which has excluded from their profession many who could have succeeded perfectly well in it. The lecturer argues that his proposal therefore has not-inconsiderable **social** implications; for CFD, when used as a teaching tool, has graphical-display capabilities which render **its** predictions very easy to comprehend physically by all.

How

Traditional-style teachers use traditional-style text-books because they are available; whereas the equivalent CFD-based tools are not (yet). Available general-purpose CFD codes could in principle be used; but only after immense labour; for the necessary so-called 'middle-ware' has been lacking.

The present lecture argues that the middle-ware, when confined to only what is needed, is not hard to create; and by **the teachers themselves** rather than less-likely-to-be-interested CFD specialists.

'Simulet' examples (*i.e.* small simulation packages) will be described and demonstrated. These focus topics of textbook-chapter size (*e.g.* pipe flow, finned surfaces, radiative heat exchange). They show conformity with functional analysis for the idealised situations to which that can be applied; but they show how numerical analysis can handle practical situations which functional analysis cannot reach.

Simulets do make use of general-purpose computer codes as their hidden engines; but neither teacher nor student needs to be aware of the fact.

No computer more powerful than a 'netbook' is required.

When

The lecturer argues that the time to exploit the new capabilities is **now**; and, not himself having very much time left, will welcome collaborators who share his desire to produce as many simulets for teachers' as possible in the next very few years.

1. INTRODUCTION

Traditional textbooks on heat transfer and fluid flow make much use of 'functional analysis' *i.e.* the mathematical techniques which derive solutions of differential equations in terms of exponential, logarithmic, trigonometric and other functions. Thus the effectiveness of a counter-flow heat exchanger is commonly expressed in terms of $e^{-Ntu(1-Cmin/Cmax)}$ where *Ntu* is the number of transfer units and *Cmin* and *Cmax* are the mass-flow-rate*specific-heat products of the two streams.

Textbook writers thus **take for granted** that their readers have sufficient understanding of differential calculus to follow the derivation and the result; and sufficient imagination to interpret mathematical revelations in physical terms, aided by such verbal explanation as their text supplies.

Two quite disparate aspects of this observation are relevant to the argument of the present paper, namely:

- the textbook writers **can** take it for granted, because would-be students who could **not** handle functional analysis have been **barred,** by entrance examinations, from embarking on any engineering course at all;
- the solutions referred to are of only **limited usefulness** for practising engineers because the assumptions on which the equations are based (*i.e.* one-dimensional-flow

and uniform-heat-transfer-coefficient) **hardly ever occur** in practice.

In regard to the second aspect it must be remarked that, precisely because of their lack of realism, the textbook formulae are used in engineering practice only for preliminary order-of-magnitude designs. Whenever reliable and economical performance is required, design studies are based on CFD simulations. Therefore it is desirable that the teaching of heat transfer and fluid flow to students should be similarly based.

That being so, the first aspect raises the question: **why** should would-be students be prevented from entering a profession for not possessing what the profession no longer requires?

Indeed, if teaching about heat exchangers 'took for granted' that the students understood the rudiments of **numerical** analysis as embodied in **CFD,** what is revealed to students about heat-exchanger effectiveness would be **more useful** to engineers; and it would also be **easily understood** by students lacking functional-analysis capabilities. Then CFD-using teachers could supplement their verbal explanations with visual ones.

The present paper will not further develop this implied criticism of traditional engineering education in general, except by remarking that educators have not at all changed their student-admission procedures to accord with the changes in engineering practice. Instead it will stress that to be prepared for learning about fluid mechanics and heat transfer by way of CFD, one must grasp only:

(1) the conservation laws of mass, momentum and energy
(2) the flux concepts of heat conduction, diffusion and viscous action; and
(3) the mathematical methods of the miser, who counts what comes in and goes out, and who checks continually what he still holds.

Section 2, which now follows, suggests how taking familiarity with CFD for granted might change teaching about **heat exchangers**. But this is just an example, from a large range of topics which might have been selected:- conduction in fins; forced and free convection inside and outside tubes; condensation and vaporisation inside and outside tubes; radiative exchange; indeed almost any topic which features in a heat-transfer textbook

Thereafter, in section 3, some details will be given of the tools which are needed and of how they can be acquired.

2. CFD-BASED TEACHING ABOUT HEAT EXCHANGERS

2.1 The tools required

The lecturer will require a lap-top computer which can project its display on to a wider screen visible to the audience. The software on his machine will include:

- a flow-simulating software package acting as a 'CFD engine', of which he needs to know nothing more than that it exists;
- a heat-exchanger-specific simulet file which he may have created for himself, but has more probably drawn from one of the many 'simulet banks' to be found (in the future) on Internet;
- a simulet-handler' package, which he uses first to select from the simulet's total offerings those which he needs for today's lecture, and then interactively during the conduct of that lecture.

2.2 How the tools might be used

The lecturer's first display could be as shown in Figure 1, below.

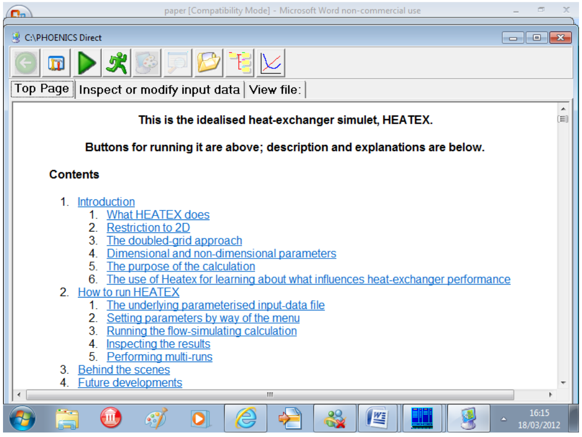


Figure 1 The start of the simulet-based lecture

The main part of the screen shown in Fig.1 evidently comprises the start of an html file, the various parts of which the lecturer will be able to display as though he were using a browser. He might wish at once to explain his intentions by displaying some of the images in it, such as Figure 2 which depicts a shell-and-tube heat exchanger and Figure 3 which explains that he will, for clarity, be representing the conditions in the shell and tube fluids side-by side; and he may return to it at any point to find pictures to illustrate his words.

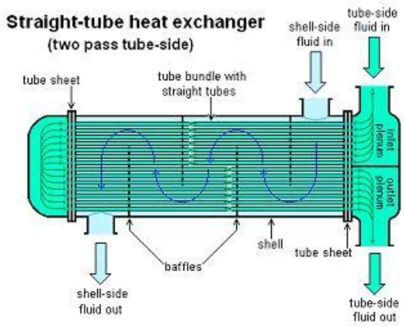


Figure 2 Heat-exchanger illustration

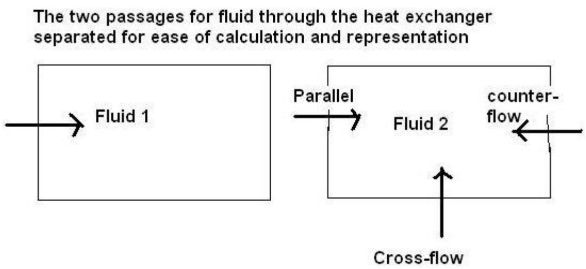


Figure 3 How the two fluids will be shown

However, the buttons and tabs at the top of the simulet-handler's screen enable him to do much more: namely to perform simulation runs in front of the class, perhaps inviting its members to propose the condition-defining parameters. These he chooses by clicking on the *'Inspect or modify input data'* tab, thereby eliciting the screen shown in Figure 4, which enables the choice of flow configuration to be made. What the first three flow configurations signify (parallel, counter, cross) signify has already been shown by Figure 3; and what the final four imply is shown by the computer-generated vector diagrams of Figure 5.

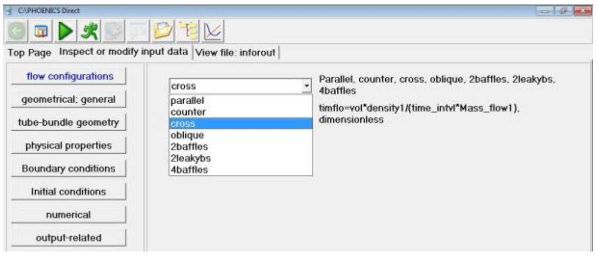


Figure 4 Menu for choosing flow configuration

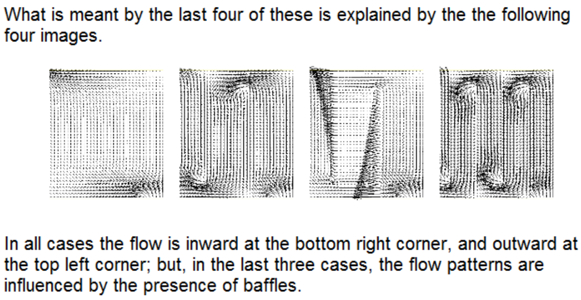
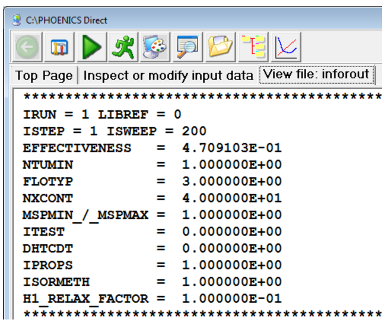


Figure 5 Oblique, 2-baffles, leaks, 4 baffles

Other parameter-setting opportunities are presented by the boxes on the left, of Figure 4, concerned with flow configuration, geometry, physical properties, boundary conditions, *etcetera*; but the lecturer might well wish to satisfy his audience's curiosity at once by saying:"Let's see what happens when we make a run with the default settings". Then he will simply click on the top-left green arrow which will cause the flow-simulating run to be performed before his students' eyes. After a few tens of seconds, during which various interesting words and images appear on the screen, the run will come to an end, and the screen will show what appears in Fig 6 below.

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**********************************************
IRUN = 1 LIBREF = 0
ISTEP = 1 ISWEEP = 200
EFFECTIVENESS   =  4.709103E-01
NTUMIN          =  1.000000E+00
FLOTYP          =  3.000000E+00
NXCONT          =  4.000000E+01
MSPMIN_/_MSPMAX =  1.000000E+00
ITEST           =  0.000000E+00
DHTCDT          =  0.000000E+00
IPROPS          =  1.000000E+00
ISORMETH        =  1.000000E+00
H1_RELAX_FACTOR =  1.000000E-01
**********************************************
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Figure 6 Selected alphanumeric data

CFD computer codes often print very large alphanumeric RESULT files, which contain far more information than anyone can easily absorb; therefore the deviser of the simulet will have made arrangements to print a single small file, containing only the most interesting items of output and input. Figure 6 therefore contains prominently the computed effectiveness (=0.4709) and records that the Number of Transfer Units and the mass_flow*specific_heat ratio were both unity. At this point the lecturer may wish to advise his students to look in a traditional text book [1] They will find there a table or graph which shows that the commonly-accepted 'exact' value of the effectiveness for these conditions is 0.476.

The difference between 0.4709 and 0.476 requires comment; it is of course to be explained by the fact that **numerical** analysis, *i.e.* CFD, perforce uses a **finite** computational-cell size, whereas **functional** analysis considers, in effect, cells of **infinitesimal** magnitude. This fact the lecturer can expand upon or dismiss according to his view of its importance.

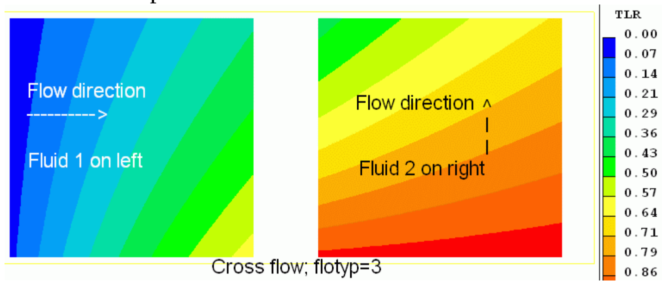

Figure 7 Temperature contours in the 2 fluids

The just-alluded-to tables and graphs of the traditional textbook contain correct information; but they can hardly be said to give their readers an intuitive 'feel for' the phenomena which they represent. By contrast, the visual-display facilities of CFD (sometimes scathingly spelled out as 'Colourful Fluid Dynamics' for that very reason) are more simulating to the imagination, as Figure 7 illustrates. Its contour diagrams show how unevenly, in a cross-flow heat exchanger, the colder fluid is heated as it flows from left to right; and how unevenly the hotter fluid is cooled, as it flows from bottom to top.

The lesson is a valuable one, particularly if the lecturer swiftly repeats the calculation with different values of NTU and mass-specific-heat ratio, which repetition the simulet makes easy. The parameters are changed by way of the menus evoked by the left-hand boxes of Figure 4; and the contour diagrams appear automatically when the middle icon in the top row of Figure 6 is repeatedly clicked, because the appropriate display-device 'macro' files have been provided by the simulet designer.

The number of variants which the simulet allows is far too great to be exhaustively described in the present paper. This section will therefore be concluded by the presentation of results for only one more case, namely that characterised by:

- the two-baffle configuration (second from the left in Figure 5); and
- a **temperature-dependent** overall heat-transfer coefficient.

The lecturer can perform the runs in front of his students, with results as shown in Figures 8 and 9; and he can invite them thereafter to explain, if they can, why the results are as they are. He will then have to disclose that there are no traditional textbooks to which they can turn for the 'right' answer; for functional analysis **is incapable of handling** cases of even this modest complexity.

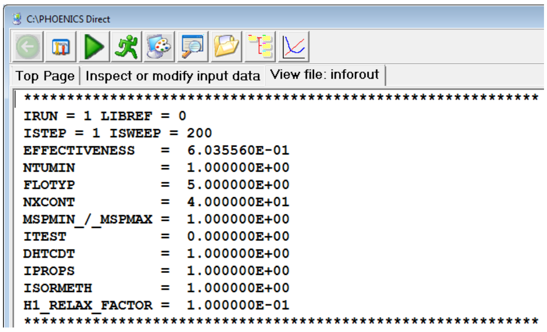

Figure 8 Alphanumeric output

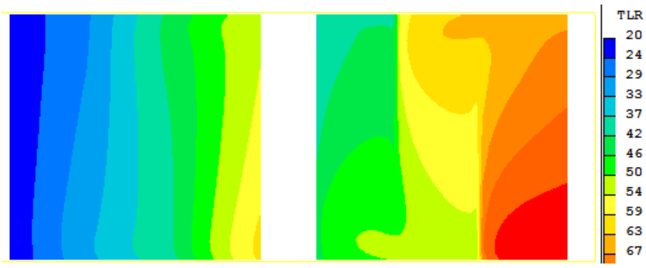

Figure 9 Temperature contours

NTU and mass-specific-heat ratio were not among the parameters modified in this case; yet Figures 8 and 9 differ considerably from Figures 6 and 7. Figure 9 reveals that the baffles have caused a somewhat-striated temperature distribution on the right-hand (shell) side. Figure 8 shows that the effectiveness is considerably larger than before; but whether that is due to the average increase in heat-transfer coefficient or to the baffling cannot at once be known. Further runs in which the parameter changes are made separately can clarify this question however; and the flexibility and speed of response of the simulet allows such questions to be answered swiftly.

The lecturer will however have neither time nor desire to make many runs in the class-room; for it is better that the students, at their own pace and following their own lines of inquiry, explore the possible variants in a later 'computer-workshop' session. Home-work assignments will be such as to require such explorations; and the drawing of conclusions from their findings. When running a case they have only to make entries into the simple-to-use menu; their full attention can therefore be given to inspecting and interpreting the results. It is these homework sessions which will constitute the main learning experience.

Much more could be presented about the teaching potential of the HEATEX simulet; but it is hoped that the above makes plausible the contention that lecturing with the **aid** of CFD can convey more-useful knowledge about heat exchangers, and more effectively, than teaching of the traditional kind.

2.3 What the lecturer has taken for granted

The imagined lecturer of the preceding section has **used** CFD; but he has not needed to **explain** it, any more than the traditional teacher of heat transfer spends time on explaining the principles of differential calculus. He has taken for granted that his audience knows, from earlier schooling that:

- the laws of conservation of mass, momentum and energy can be applied to finite bodies of matter;
- that they can also be applied to 'control volumes', through the boundaries of which material can flow, carrying its momentum and energy with it;
- that conductive-diffusive fluxes of mass species, of energy and of momentum can also cross these boundaries as a result of differences across the boundaries of concentration, temperature and velocity; and that there can be sources and sinks of the conserved entities, inside the control volumes, associated with body forces, ohmic heating, and other phenomena;
- that, when analysing what occurs within large bodies of material it is useful to split them up into orderly arrays of contiguous control volumes, sometimes called a 'mesh' or a 'grid', the control volumes then often being called 'cells'; and
- that if the conservation equations are applied systematically to all the cells, and the resulting algebraic equations somehow solved, the resulting cell temperatures, velocities, *etcetera*, represent conditions within the bodies approximately, and perhaps well enough.

The **methods** by which the equations are solved is a specialist subject, of which the non-specialist will know only as much as he needs to know, namely:

- that they exist, and are built into the underlying 'CFD engine';
- that they usually involve **successive-approximation** procedures which, when repeated enough times, called 'iterations', 'converge' to a final solution;
- that they are therefore laborious, which is why computers are used for their execution; and
- that their accuracy depends on the fineness of the grid which has been chosen and the number of iterations employed.

The lecturer may wish, from time to time, to remind the students of these facts by displaying the grids and iteration numbers which he has employed; and setting home-work tasks of the kind: "Explore the influence of grid size and iteration number on the predicted effectiveness of a heat-exchanger with the following flow configuration and boundary conditions". The HEATEX simulet allows this, being in this respect far removed from being the impenetrable 'black box' which causes some onlookers to voice fears about the dangers of over-reliance on computers in education. Indeed it enables the user to understand clearly the **approximate** character of CFD. And he will be a rare student who is not forced to recognise that human error in respect of data input sometimes produces wholly implausible results.

However, the important point to recognise is that the lecturer is **only reminding** them of what they have learned elsewhere; and that he can rely on the fact that his students are also attending other classes in which their basic CFD knowledge is being either similarly relied upon or imparted.

3. PRACTICALITIES

The remainder of the paper is written for readers who, persuaded that the advocated teaching method is worth trying, ask: "How can I begin?"

3.1 The components of a simulet

The general simulet idea is not confined to any particular CFD code. One of the current commercial codes could be used, or any other to which a reader has access, provided only that it possesses a '**parameterised data-input'** system. The HEATEX simulet which has been described employs PHOENICS as its 'CFD engine'; its files are therefore written in the PHOENICS Input Language known as PIL; but anyone who knows both PIL and the input language of the AnyOther code, will no doubt be able to create a translation package. Therefore from this point onwards, wherever exemplification is needed, it will be in PHOENICS terms.

The parameterised input file

The whole specific content of the HEATEX simulet is contained in a human-readable ASCII-text input file consisting of three parts:

- Part 1, which declares the parameters which are required to define the phenomena to be simulated, and assigns default values to them;
- Part 2, which contains only the command to load a file called FromMenu.htm, so as to read from it any parameters which the menu user has decided upon;
- Part 3, which contains PIL statements which translate the parameter settings into instructions which the CFD-engine will obey.

Part 1, the declare-and-set part, can be written by anyone who learns the following simple elements of PIL:

1. That a real variable named *inletvel* is declared, explained and given the default value 10.0 by the lines:
   Real(inletvel) ! inlet velocity in m/s
   Inletvel=10.
2. That an integer variable named *iprops* is declared, explained and given the default value *1* (meaning 'uniform properties') by the lines:
   Integer(iprops) ! uniformity-of-properties index
   Iprops=1
3. That a character variable named *flocon* is declared, explained and given the default value *4baffles* by the lines:
   Char(flocon) ! flow configuration
   Flocon=4baffles
4. And that a logical variable named *comprs* is declared, explained and given the default value *F* (meaning false) by the lines:
   Boolean(comprs) ! compressible-flow indicator
   Comprs=F

These variables, by the way, are not pre-ordained entities which their users have had to learn about. They are rather the user's own inventions. Once he has decided what parameters are needed for defining his simulation scenario, he can use any words which he likes. For the sake of orderliness, the parameters will probably be collected into groups of similar significance, for example:

- geometrical, including the sizes of the domain and of objects within it, and of where they are to be placed in relation to one another;
- physical processes, including properties, such as thermal conductivity, specific heat and viscosity of the materials in question;
- initial conditions, such as starting distributions of temperature and pressure;
- boundary conditions, such as flow rates of material at inlets and outlets, and incoming radiation fluxes from outside the domain;
- numerical settings related to grid fineness and iteration number; and
- output-related settings such as what to print in the short-summary alphanumeric file.

These somewhat-banal statements have not been made simply to make plain that commonsense is all that is required. It is not hard for any teacher to conceive and initiate a simulet; but help may be needed from the PIL (or AnyOther language) expert before it can take final shape.

The menu-managing executable

A simulet may have many hundreds of parameters which collectively define its possible scenarios; which is too many for an effective teaching session; and the parameterised input file itself would be dauntingly over-complex for any student and indeed for most lecturers. Therefore the simulet-managing executable has **two** modes of operation: one for the student and one for the teacher.

The teacher uses the manager in order to decide which of the many parameters to make accessible to the students for his present purpose. The student is thus enabled and invited to explore the influences of only those parameters which the teacher has selected. Thus, in successive lectures and workshop sessions, attention might be focussed first on the influence of the flow configuration, then on material-property aspects, and later on how the performance prediction depends upon non-physical numerical settings. The student is thus introduced to the individual aspects of the subject of study in an orderly way.

The display-package macros

There are many excellent graphical-display packages which represent the results of CFD calculations *via*:- animated streamline plots, constant-value surfaces, contour plots, vector diagrams and other informative devices. However, their possibilities are so great that to expect a student to find out how to use them is to waste much of his time. Therefore the simulet philosophy, which favours focussing and discourages distractions, requires that so-called 'macros' are provided which reveal immediately those features of the results which the teacher deems most worthy of consideration.

Such macros are commonly text files containing lines of instruction to the display package which have the same effects as would icon-clicks and scroll-bar movements performed interactively by the human operator of a mouse or keyboard.

Most display packages have macro facilities; but their existence is not always well publicised. Indeed it sometimes seems as though the package creators, being enamoured of their products, are impatient with users who are not enthusiastic enough to learn how to use the packages 'properly'.

The student who **has** had the opportunity to learn more of the packages' capabilities can still exploit that knowledge; but, by using macros which are provided as parts of the simulet, the less-knowledgeable student can absorb at least the main message which the teacher wishes to convey.

Multi-run capability

Often it is necessary to conduct a series of runs in order that the practically important lessons are learned, for example concerning how the effectiveness of a heat exchanger, of given flow configuration, depends on the two parameters: Number of Transfer Units and mass-flow-times-specific-heat ratio. Of course, such a series of runs could be launched one-by-one by any individual; but this would not be a good use of his time.

An efficient simulet manager therefore allows its user to define a one-, two-more-dimensional set of parameters which to be investigated, and how the results are to be collected and presented in an easily understandable manner. The manager which the author has been using possesses such a feature. Those who have experienced its utility sometimes become disinclined ever to do single runs again.

Multi-language capability

The simulet manager is also, it should be mentioned, capable of handling other character sets than the Latin one shown in the above figures. Cyrillic, Japanese, Chinese and Arabic character sets are among those which can be used. Therefore the simulet-using and –creating community can become a truly international one.

3.2 A simulet-sharing club

"An interesting idea", some may conclude, "I will use simulets when they are available; and I would like to make some myself; and share them with other teachers throughout the world".

It is to those who have this reaction that the final paragraphs of the present lecture are addressed, with special attention to the word "share". For the desirable availability of an array of simulets which collectively cover all aspects of heat transfer and fluid flow will not come about without the combined efforts of many like-minded educators.

Such collaboration requires the wide acceptance of a unique format in order that exchanges are easily made; and it is here suggested that the form of simulet described above is sufficiently simple and flexible as a model to be copied. It also needs some motivational mechanism, whereby those who benefit from the contributions of others make some small return; and indeed are encouraged by the prospect of rewards for themselves to make contributions of their own.

Perhaps, as indicated by the above heading, the 'club' concept will serve. For this reason the author closes this lecture with an invitation to interested members of the audience, and to readers of the printed version, to indicate their desire to participate in creating what might turn out to be a valuable educational asset.

Such things do happen; and a Simulet Society, although it may not attain the popularity of Facebook, may still spread quite quickly across the world.

4. REFERENCES

[1] Kays, W. and London, A. L., Compact Heat Exchangers, McGraw Hill, 1964.

5. ACKNOWLEDGEMENTS

The software package referred to above as the 'simulet-manager' is the brain-child of Dr. Alexey Ginevsky, of the Moscow Power-Engineering Institute. The author expresses his gratitude to him; and also to Dr Elena Pankova who has participated in the creation and testing of the HEATEX package, of which some results have been displayed above.