Some Reflections on Progress in Engineering Heat Transfer

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LECTURE

1. INTRODUCTION

The science of engineering heat transfer, as we know it today, is now some fifty years old. The physical principles of conduction, convection and radiation were established much earlier, but papers dealing with their application to engineering problems began to appear in numbers in the 1920's and increased rapidly in the 1930's. The number of publications each year is still rising today, the present conference, for example, having 125 papers, compared to 83 in the 1951 conference. Yet no basically new method of heat transfer has so far been discovered, and no new physical principals are involved; we are still exploring the many varieties and combinations of conduction, convection and radiation. The practical importance of the subject is still very great both in the older industries and in new engineering developments, and thus there is still a great deal to be done despite the extensive research effort which has been, and is still being, made in many countries.

The other three review lectures in this conference have given authoritative accounts of progress in three main fields of forced convection, free convection, and radiation. This leaves me with no particular broad area of the subject to review, and I should like instead to reflect on the progress which has been made in recent years, particularly from the point of view of the practical application of heat transfer research to the improvement of the performance of industrial appliances.

It appears to me that there is still a wide gap between the research work which is being done in universities, government establishments and in industry, and the effective use of the results of this work in the design of better heat exchange plant. Naturally there are exceptions, and the use which is made of research is greater in some industries than in others, but on the whole industrial application lags a long way behind research, and it may be worth considering to what extent improvement in existing appliances, or their replacement by better ones, is possible; and, if it is possible, how research can be utilised more effectively and more rapidly.

2. THE AIMS OF HEAT TRANSFER SCIENCE

Engineering heat transfer is a science of calculation, that is to say, its aim is to establish an adequate background of quantitative knowledge to enable the designer to calculate the heat transfer and temperature under given conditions. In passing it is therefore worth remembering that striving for excessive accuracy in research may be misplaced effort unless the accuracy of any foreseeable application justifies it. For example, I doubt whether the use of terms containing up to fifty significant figures, leading to the calculation of Eigen functions to eight decimal places in a recent paper on Heat Transfer in Laminar Flow in a Conduit, is justified as a contribution to engineering heat transfer.

The greatest difficulty in applying existing knowledge of heat transfer to design is that, due to practical considerations of construction and materials, the conditions in an actual appliance differ from the idealised conditions assumed in theories or defined in the controlled experiments of the laboratory. The conditions vary from one design to another, and in many cases it is difficult even to specify them in suitable terms. Of course a similar situation exists in all engineering sciences, but heat transfer is one of the most difficult because of its complexity. Examples of difficulty in specifying conditions are internal surface irregularities due to joints and welds, deposits, varieties of surface temperature distributions due to complex heat flow in a structure, cross-sectional velocity or temperature distributions at the entry to a duct and other flow irregularities. As a result of such difficulties it is often difficult to relate the results of tests on actual appliances with fundamental data obtained in the laboratory.

The idealistic approach, in which the research worker's aim is to establish data adequate for a completely ab initio design of all heat transfer appliances, is to some extent a myth. It is highly unlikely that we shall in any reasonable period of time, establish sufficient data for designing even simple appliances in this way. In any case there are quicker and more effective ways of arriving at the best answer, by utilising the knowledge gained by experience of existing plant, and using the background knowledge of heat transfer science to guide us towards improvements.

3. THE PRESENT POSITION IN THE APPLICATION OF RESULTS OF HEAT TRANSFER RESEARCH TO DESIGN OF EFFICIENT HEAT EXCHANGE PLANT

Heat transfer research in recent years has led to substantial practical results in the design of new appliances, such as nuclear power plant and missiles, but has yielded relatively little improvement in older conventional plant such as boilers, condensers, heaters and coolers. One reason for this may be certain special features of some new applications, such as the absence of fouling by deposits, but another more basic reason is that designers of entirely new appliances are forced to make greater use of fundamental data and basic methods because they have no established practice to guide them. It is thus more likely that they will consider novel ideas and features. To design a completely new form of conventional plant such as, for example, a condenser, starting from first principles, would be very expensive and therefore only likely to be undertaken if there were a good prospect that the result would be a significant improvement on existing designs, which may be quite satisfactory as a result of years of development and experience. It may be difficult to make out a case in advance for the new project.

There is, however, a large return for even small improvements in conventional heat transfer appliances, because of their widespread use and expensive nature. In using the word "improvement" it must be remembered that the ultimate criterion is cost, and it is of little value, say, to improve heat transfer by methods which involve increased costs of materials, manufacturing methods, or fans for higher pressure drops, which outweigh the savings. Over the last ten years, it is probably fair to say in regard to conventional types of heat exchange plant, that

(a) very little improvement in "performance" has resulted from the great volume of heat transfer research in recent years,

(b) much research work tends to establish reasons for doing what designers already know they have to do, rather than in showing them what to do to improve the plant,

(c) large factors of ignorance, particularly for fouling, are still commonly employed, although there has been some improvement by closer design based on more scientific testing with fully instrumented test rigs.

(d) there has been improvement in the systematic handling of data, and in design techniques, by the use of computers, and also partly because personnel have become more familiar with scientific methods,

(e) more substantial improvements have come from the use of better materials and manufacturing methods, which cannot perhaps be regarded as due to heat transfer research at all. Examples are improved brazing techniques such as brazed aluminium, new methods of fabricating extended surface heat exchangers, use of copper bearing steels to combat sulphur dew point troubles, automatic welding and use of closer pitched studs, use of conduction plates to eliminate hot spots, and many other similar improvements.

(f) where new designs of plant have been produced, the heat transfer data used by designers is usually the older, well-established text-book material rather than new research results.

Perhaps the general conclusion is that the establishing of more accurate heat transfer under controlled conditions by theoretical and laboratory experimental work, although of value in systematising design techniques, does not necessarily lead to better design. If existing designs are to be improved by research, (a) more measurements must be made on actual plant, or in some cases models, to find out more about the fluid flow and heat transfer conditions as they actually occur in practice, and thus to suggest where and how they may be improved and (b) more research must be concentrated on systems of heat transfer which are novel for the particular application. Examples are evaporative cooling in turbo-alternators, continuous regeneration for use in gas turbines or any application where their basic features make them attractive versus recuperators, use of liquid metal loops in steam reheat or other suitable applications, exploitation of dropwise condensation in condensers or chemical plant, exploitation of effusion cooling, etc., etc.

In certain newer developments, notably nuclear energy and high speed flight, on the other hand, there has been more use of recent research results especially where the conditions are extreme ones, such as very high speeds, very low pressures, large temperature differences, for which research data have only recently become available. This situation is temporary, in that novel appliances rapidly become conventional, and whether this type of plant has reached a more efficient stage of development because it has been designed from research data is difficult to say, though it is certain that research has saved a great deal of time which would otherwise have been needed to develop the plant by ad hoc methods.

The important question is how far existing designs, whether of conventional or novel plant, are capable of further improvement. Some future research should be directed at answering this important question for all types of heat exchange plant.

4. METHODS OF SOLVING HEAT TRANSFER PROBLEMS

Generally speaking the means available for solving any problem in heat transfer are

(1) theoretical solution of the relevant fundamental differential equations, including use of approximate methods,

(2) use of general arguments such as dimensional analysis,

(3) experiments, which may take three forms

(a) measurements in the laboratory under deliberately controlled conditions,

(b) tests on models or analogues,

(c) measurements on actual appliances.

Each method has its usefulness, and it may be worth considering the possible role of each method in the further progress of engineering heat transfer science.

5. THEORETICAL SOLUTIONS

These have the important advantages of speed, especially by using electronic computers, and an accuracy which is usually greater than can be effectively utilised in design. Their disadvantage is that they are limited to cases where the basic equations can be written down and solved, and that they require precise specification of boundary conditions. Great progress has been made by theoretical methods in problems of conduction in solids, laminar boundary layers of all kinds including property variations with temperature and high-speed effects, and geometrical radiation problems.

Theoretical solutions of turbulent flow boundary layers necessarily involve some empirical assumptions, either in the form of eddy transport properties or velocity and temperature profiles, but their use can lead to better understanding of the effects of variables such as property variations, finite temperature differences, and non-uniform surface temperature distributions. Outside these fields, theoretical solutions generally become more difficult and usually involve selecting boundary conditions which, from experiment or general argument, are known to approximate fairly closely to what occurs in practice. Nevertheless, when this is possible, theoretical methods are extremely valuable. All theoretical methods have the disadvantage, of course, that before the results can be applied numerically the values of the relevant physical properties must be known sufficiently accurately.

Relatively little attention has been given to measuring fluid transport properties accurately in recent years, but lack of property values is perhaps less serious than appears at first sight.

For most gases the Prandtl number is known over a wide range of temperatures, usually to within from ±1% to ±3%. In forced convection, $Nu = c\,Re^{m}\,Pr^{n}$ and therefore $H \propto Pr^{n-1} / \mu^{m-1}$. Since n is usually near 0.4, $n - 1 \doteqdot - 0.6$, and the error due to uncertainty of Pr is thus small. Since $0.5 < m < 0.8$, the percentage error in H is considerably less than that in μ. The error in H due to uncertainty of fluid transport property values is thus not very great, and indeed the scatter in most correlations including that of forced convection in tubes exceeds the possible error due to fluid properties.

For liquids the Pr is known only from the separate values of c, μ, and k, and the heat transfer depends to approximately the same degree on the values of all three properties, which must be accurately known.

For natural convection in gases and liquids, on the other hand $Nu = c(Gr \cdot Pr)^{n}$ where $\frac{1}{4} < n < 1/3$, and therefore $H \propto k^{1-n} / \mu^{n}$, that is the accuracy to which k is known is 2 or 3 times as important as the accuracy of c and μ.

The most difficult matter, however, is the reference temperature in cases of large temperature differences. Even with gases the uncertainty may be very great, and further work is required especially for turbulent flows. With liquids the uncertainty of the reference temperature for μ is usually the biggest difficulty.

6. GENERAL ARGUMENTS

(a) Dimensional Analysis. Dimensional analysis played an important part in the early evolution of heat transfer science, and its use in correlation is now well known. But its use in planning and interpreting experimental work and in new problems is still sometimes not fully exploited. It may also be used in other forms. To give an example, recently it has been pointed out that, by associating variables with the three separate mutually perpendicular length directions in space, more information may be obtained than by ordinary dimensional analysis, in which the three length dimensions are indistinguishable. Thus for forced convections in flow along a flat surface, taking l_x, l_y, l_z to represent lengths measured respectively in the flow direction, perpendicular to the surface, and in the plane of the surface at right angles to the flow, the length dimensions of the usual numbers become $Re\left(\frac{l_x^2}{l_y^2}\right)$, $P\,(0)$ and $Nu\left(\frac{l_x}{l_y}\right)$, from which it immediately follows that $Nu/\sqrt{Re} = f(Pr)$ a familiar result usually obtained from the boundary layer equations. Similarly for free convection from a flat vertical plate $Nu/\sqrt[4]{Gr} = F(Pr)$. In obtaining these results it is assumed that the transport properties μ and k both have length dimensions $\dfrac{l_y}{l_x l_z}$, which is only permissible when the viscous shearing takes place between planes parallel to the surface. This is true for laminar flow, in accord with the usual assumptions implied in the boundary layer equations, but it would not be true for turbulent flow, for which of course the results are known from experiment to be incorrect. The application to cases of laminar free convection from a flat surface combined with forced convection in any direction parallel to the surface suggests $\dfrac{Nu}{\sqrt{Re}} = f\left[\dfrac{Re^2}{Gr}, Pr\right]$ which result has been used effectively in correlating experimental results. This method may also be used in some problems of rotating surfaces.

(b) The Characteristic Length in Forced Convection. As a further example of general arguments, the characteristic length in the Re number in forced convection flows appears in three different forms:

(a) length measured parallel to the direction of flow, as in all cases of boundary layer development. In these cases the exponent in the $Nu - Re$ relation is 0.5 for laminar flow, and 0.8 for the flat plate.

(b) length measured perpendicular to the flow, as in flow through a pipe. For long enough pipes, in turbulent flow, the index becomes the familiar 0.8.

(c) lengths which are really a measure of the radius of curvature of the surface, as in the case of the circular cylinder rotating about its axis, where the boundary layer does not start at any particular point of the circumference, and no length in the direction of flow can be specified, neither of course can any length perpendicular to the flow. In this case, for turbulent flow, the index in the $Nu - Re$ relation is known to be 0.66.

For laminar flows these results follow directly from the appropriate theory. For the turbulent flows the index 0.8 has no fundamental derivation, but is generally understood to be an intermediate value between 0.5 for laminar flow, as in the laminar sub-layer, and 1.0 for fully-developed turbulent flow at a distance from the surface. The precision with which experimental results conform to the 0.8 index is perhaps surprising. The near identity of the index for turbulent flow in cases (a) and (b) is accounted for on general grounds by remembering that for the flat plate the boundary layer thickness t is proportional to $l^{0.8}$, where l is length from the start of the layer, and the local Nu is proportional to ${Re_l}^{-0.2}$ or ${Re_d}^{0.75}$. If we assume that the Nu number for established flow between two parallel flat plates distance d apart corresponds to that reached for flow over a single plate at a distance $l = ½ d$, the corresponding index should then be 0.75.

In case (c) the index may actually be predicted by assuming that the length dimension d (cylinder diameter) can affect the flow only as a radius of curvature, in which case it must appear in the acceleration term V^2/d. Since from $\dfrac{Hd}{P_2\theta} = c\left(\dfrac{V\rho d}{\mu}\right)^n$, H varies as V^n/d^{1-n}, it follows that $n = 2(1-n)$ or $n = 2/3$.

7. EXPERIMENTAL METHODS

Experimental measurements of heat transfer are very difficult to carry out accurately. When a theory exists the carrying out of experiments to check it does not always lead to a satisfactory conclusion because any difference between theory and experiment is usually attributed to the experimental conditions not being precisely those assumed in the theory. A great deal of time has been wasted in such investigations. An experimental investigation is of value either (a) when there is a chance of the theory being fundamentally incorrect, which is rather rare in heat transfer or (b) the conditions of the experiment are too difficult for theoretical treatment. A great deal of work has been done in fields such as boiling heat transfer, neither giving results in a form which can be generalised by theory, nor representing conditions actually encountered in practice.

The use of analogues and models has on the whole not made many major contributions to heat transfer. As has already been said, analogues which simulate differential equations and are used for problems where the conditions are fully specified, are often inferior to computational methods today. Analogues which are used to simulate the complicated unknown conditions of actual appliances, that is true dynamically similar models, may be of great value since they are smaller and cheaper to build than the full-scale appliances, but it is often difficult to ensure that the important conditions of the full-scale have been adequately reproduced in the model.

Experimental investigations on full-scale or near full-scale appliances, seem to offer one of the most important ways of future progress, and improvement of performances of heat transfer appliances generally. By more intensive study of the conditions in actual plant their performance may be related to theoretical data, and the scope remaining for further improvements determined. Where practically no such scope exists, it is not much use hoping for further results from application of research. By such measurements, for example in internal combustion engines, boiler furnaces, rocket chambers, wind tunnels, etc., it should be possible to find what are the important factors, to isolate parts of the problem for study by theory or controlled experiments. Such investigations seem to be the immediate need in heat transfer research rather than many more controlled conditions laboratory investigations, the results of which cannot easily be translated into practice as they stand. The regions in which research could be profitably applied in the future could thus be highlighted and work concentrated upon them.

The possibility of discovery of some new process of heat transfer cannot be entirely discounted, and fundamental work of this kind is important.

8. CONCLUSION

In his review lecture at the 1951 Conference in London, the late A. P. Colburn concluded "the basic theory underlying condensation of pure and mixed vapours has been fairly well developed, and heat and mass transfer rates have been established for simple shapes. Considerably more attention needs to be given to methods of utilizing this information in design, both for accurate and approximate answers". These words, which Colburn spoke with reference to heat transfer from condensing vapours, are still true today over the wider field of heat transfer. To achieve the most rapid progress, more attempts must be made to relate laboratory experiments and theoretical analyses to the conditions met with in practice. Aided by the developments which have occurred in recent years in measuring techniques this should be possible. Research workers should also be encouraged to take more interest in the practical usefulness of their studies and in their economic significance. All resources and methods, theoretical and experimental, analytical and statistical, laboratory and full scale, must be linked together to solve the problems of better design for industry.