Int. J. Heat Mass Transfer. Vol. 18, pp. 1223–1227. Pergamon Press 1975. Printed in Great Britain

FURTHER COMMENTS ON HEAT TRANSFER RESEARCH

R. H. SABERSKY
California Institute of Technology, Pasadena, CA 91109, U.S.A.

(*Received* 19 *February* 1975 *and in revised form* 25 *February* 1975)

(A) INTRODUCTION

IN THE December 1971 issue of the *International Journal of Heat and Mass Transfer* a survey article was published entitled "Heat transfer research in the Seventies [1]". That article summarized the views and opinions of many experts on important subjects for future research in Heat and Mass Transfer. The opinions were obtained through extensive correspondence, through a number of informal meetings, and through a Round Table Session which was held at the 4th International Heat Transfer Conference in Versailles. A similar Round Table Session was arranged for the 5th International Heat Transfer Conference in Tokyo [2]. In preparation for that Session many experts were again consulted. They were asked in particular to comment on the material in the earlier publication and to suggest additions, deletions, or changes in emphasis as to the recommended areas of research. Further discussion then took place at the Round Table Session itself.

The purpose of the present paper is to summarize the information that was developed at the 1974 Round Table Session as well as in preparation for that session. The material to be presented is to be considered jointly with that in the earlier paper, and the present report is meant to supplement and not to supersede the one published in 1971.

(B) FURTHER COMMENTS ON FUTURE RESEARCH

The comments that have been received may be conveniently arranged under several subheadings, each indicating a general field of interest.

1. *Nuclear fusion*

The generation of power by nuclear fusion has progressed quite slowly; yet it now has advanced to the stage where serious consideration is being given to the engineering problems involved in converting the heat released by fusion into electric power. The problems that arise primarily involve the use of liquid metals and the effects of very strong electric and magnetic fields. Particular problems cited by workers in the field are the following:

(a) The effect of magnetic fields on turbulent flow, the possibility of relaminarization and the role of the Reynolds number and the Hartman number on this process. Experimental work in particular was recommended.

(b) Some concepts envision heat removal through boiling of potassium, again in the presence of very high magnetic fields. Now anyone who has worked in either boiling, or liquid metals, or MHD knows that each subject separately offers extreme difficulties, and the challenge to predict the behavior of a boiling liquid metal under the influence of magnetic fields is indeed staggering!

(c) Certain concepts involve the use of lithium in free convection, and also as a falling film. Again these conditions are to be investigated including, of course, the effects of the electromagnetic fields.

(d) Finally there is a need for the radiation properties of the wall material for a wide range of pertinent wavelengths.

In studying the heat-transfer problems, it has to be realized, however, that the allowable temperatures and heat-transfer rates may have to be severely restricted by considerations of reliability, endurance, corrosion, and material compatibility. The limits imposed by these factors may reduce the requirements of the heat removal system and may possibly simplify the task of developing the necessary heat-transfer design information.

2. *Nuclear fission*

Problems relating to nuclear fission were considered in the last review and, in fact, it was stated that the research needs in this area were well known. However, several respondents stressed the need for additional and continued investigations. It is interesting to note that essentially all of the new comments were related to safety. Particular recommendations for further investigations were concerned with (a) off-normal operating conditions, (b) boiling transients, (c) boiling and two-phase flow as a result of depressurization, (d) the effect of vibrations on reactor heat transfer, and (e) the phenomena occurring when coolant contacts molten metal during an accident.

The question of modeling was also raised and there seems to be a difference of opinion on its usefulness in studying transient phenomena as they may occur during an accident, and during emergency cooling. Some seem to feel that much can be learned from models which may involve different geometrical scale and different fluids. Others are quite skeptical and feel that full-scale testing of these phenomena is unavoidable. Further work to assess the feasibility of modeling is indicated, particularly as successful modeling could drastically reduce the costs which would otherwise be incurred for full-scale tests.

3. *Energy*

It is not surprising that a number of responses had reference to the production and conservation of energy. The need for further development of heat exchangers was pointed out in connection with several separate applications. In the process industry steam and water are now used frequently as heat sources and sinks. In the future the process streams themselves, may be required to serve this need and this, in turn, will require the development of specialized heat exchange systems. Large air heat-exchangers, such as those for dry cooling towers, may also be required. To make such designs feasible, more effective surfaces will have to be developed and this will require further studies of fin-arrangements and other heat-transfer augmenters. The investigations of augmenters in particular should be extended to laminar flows, which is an important flow regime in these applications. The further development of heat pumps for space heating and airconditioning also will depend largely on the development of effective and economic heat exchangers. Similarly the exploitation of small temperature differences in the ocean for the purpose of power production may depend to a significant degree on the development of heat exchangers. For the extraction of energy from geothermal sources, finally, the heat exchanger may again be one of the key components. In this application the exchanger most importantly will have to resist fouling, and this requirement may give additional emphasis to this intricate problem.

Aside from these specialized needs, further study and development was recommended for the so-called "common" types of heat exchangers used in the power and process industry. Even though this topic was discussed in the 1971 report, the comments referring to common heat exchangers exceeded in number those for any other single subject. Tube vibration and again fouling were considered to be the problems deserving the most attention.

Packed and fluidized beds may play a role in coal gassification and shale oil recovery, and they will continue to be important elements in a number of other chemical processes. Further study of the complicated transport mechanisms in such beds and the development of design information is certainly warranted. Heat transfer to flowing granular media, and the heat exchange between two distinct types of granular media in a retort may also be of importance in future processes, and deserve attention.

In addition to the suggestions related to individual components and processes, renewed systems studies were recommended of the energy balance for buildings, factories, power plants, and similar units. With the new valuation of energy, this could well lead to novel designs and approaches.

4. *Food and food processing*

The crucial importance of world-wide supply of food—the fuel for living beings—has been recognized and more intensive efforts to enhance food production and food processing will certainly be forthcoming. Many of the problems to be solved are in the field of heat and mass transfer, and the following were proposed in addition to those listed in the previous report.

(a) Further exploration of the use of solar energy for the raising of crops and for the prevention of disease. The first could include such approaches as more extensive or more sophisticated uses of the greenhouse effect. The second envisions, for example, further studies of the radiation characteristics of crops exposed to sunlight. The temperature cycle of the crops could then be predicted and this cycle could be important in determining the crops resistance to certain pests and diseases. With this information, favored locations could be selected more effectively or the desired "microclimate" may even be provided by artificial means.

(b) Perhaps one of the most important problems concerns the drying of crops immediately after harvest. Because of adverse conditions in some agricultural regions of the world, large portions of the crop are lost at this stage. Further study of the drying mechanism as well as of the prevailing local conditions could conceivably lead to a significant reduction of the crop loss. The solution of this problem could well have a major impact on food production in several agricultural regions.

(c) With the increasing cost of fuel it may again become advantageous to dry crops such as raisins, apricots, and prunes by sunlight. This, in fact, could be one of the applications in which solar energy could be substituted most easily for other sources of energy. Further study of the drying process is indicated so that it may be carried out within a space and within a time period which are economical.

There was some mention of this type of problem in the previous report in connection with the drying of sisal. This example, in fact, illustrated the kind of special problem which may arise in a process which appears to be perfectly straight forward. The drying of this crop by direct sunlight produced discoloration and this could be avoided by filtering out the ultraviolet radiation.

(d) Almost all foods in the course of preservation and preparation are being "heat-treated" in some manner. It may be expected that these treatments will be performed on even larger industrial scales, and there will be increased emphasis on carrying out the processes in an efficient and economical manner. This, in turn, will require a more complete understanding of the physical and chemical mechanisms involved. The thermal treatments to be considered include cooking, freezing, freezing by liquid N_2, dehydration, spray drying and freeze drying. To be able to study the pertinent processes it is, of course, necessary to obtain data for the properties of the substances involved. These properties are difficult to determine, in particular, as many of the substances will undergo large changes in moisture content and many of the properties are likely to be moisture dependent. The problem of analyzing the process is complicated further by the fact that in many instances the substances change phase.

Work on all of the above problems is proceeding. So far, however, only relatively few experts in heat and mass transfer have been involved. The problems are most challenging and to be able to contribute to this important task of food production should be most gratifying.

5. *Fire prevention and control*

Additional suggestions were offered for studies related to the prevention or control of fires; in particular, the following topics were cited:

(a) Fire involving fuel spills as a result of an accident including accidents with cars and airplanes, the rupture of fuel tanks (including liquid natural gas), as well as fires in oil wells.

(b) The development of representative testing methods of the resistance of materials to fire. This point, although included in the previous report was stressed again. One reason for this continued emphasis may be the fact that it has been realized that some of the standard tests are quite misleading as to the flammability of some plastic materials. In addition it has become widely known that the standard tests established in various different countries lead to widely different conclusions.

(c) The continued development of fire resistant structural components, such as the water-cooled reinforced concrete column.

(d) Continued investigation of the radiation by flames as they occur in fire and the free convection heat transfer that results from a fire.

These studies are to provide rather accurate data on emissivities and convection coefficients so that the rate of spreading of a fire may be predicted in a more satisfactory manner. The need for accuracy comes from the desire to design and furnish buildings and structures in such a way as to limit possible fire damage. Should a fire start, therefore, its rate of spreading should be sufficiently slow, so that it can be extinguished before it can cause any major destruction. The difference between 15 and 20 min in this allowable time may be very significant. This, in turn, means that the overall ignition process should be predictable within 25 per cent or so, and the individual steps of the process (e.g. the radiation) will have to be predictable within narrower limits.

6. *Lasers*

The development and application of lasers continues to grow, and proper temperature control is a factor in the design of the instrument itself which requires uniform temperatures to minimize changes of optical parameters in the lazing medium as well as to prevent distortion of the windows and mirrors. Perhaps even more challenging, however, is the possibility of directing the laser beam by the use of gaseous windows, light guides and lenses. This idea of controlling a gaseous body to obtain desired optical effects is a most interesting one. Professor Luikov, who has stressed the importance of this field, has even suggested that it deserves a special name and has proposed the word "Aerothermooptics".

7. *Arc technology and plasma heat transfer*

In the decade of the sixties studies on electric arcs and plasmas were conducted mainly under the auspices of space exploration. It is often forgotten that arc technology enters many other applications. Some examples include plasma torches for material processing (melting, welding, sphereodizing, etc.). Circuit breakers, arc light sources, and arc gas heaters for chemical processing and material testing. Advances in our understanding of the complex processes in arc plasmas will benefit all of the foregoing applications and further study of this field is certainly in order. Some specific aspects that will require investigation concern the interaction of arc plasmas with flowing fluids, the thermodynamic state of the plasma, and the interaction between plasmas and solid surfaces. The latter case can result in extremely high heat transfer rates, with rates of 10^6 W/cm^2 being mentioned.

8. *Heat pipes*

Heat pipes were considered in the previous report, however, from the comments received it was clear that they deserve additional emphasis. There are now a number of applications in which heat pipes have been used advantageously. Among these are (a) heat exchangers in large heating and ventilating systems (b) permafrost control–Alaskan pipe line (c) cryoprobes in surgery and (d) spacecraft temperature control.

Optimizing the heat pipe performance for these and other proposed applications involves several aspects. Among the problems requiring further attention in particular are those related to the transport of the condensed liquid to the evaporator area. The problem is acute for fluids with low heat of evaporation and low surface tension and some of the applications, particularly those involving very low temperatures, require just such fluids.

A set of most interesting problems also arises from the use of heat pipes containing multicomponent fluids. These fluids are intended to give the heat pipe certain special characteristics, for example heat transfer in one direction only. The study of the behavior of these fluids involving two phases and two or more components offers very appropriate research opportunities.

9. *Basic problems*

The importance of continued study of basic problems and mechanisms was stressed and several specific examples were given.

(a) The more detailed study of the combined transfer of heat and mass and the inclusion of the effects of non-equilibrium thermodynamics, such as the mass transfer due to temperature gradients.

(b) The extension of certain basic problems in heat and mass transfer so as to fulfill more realistic boundary conditions. As an example of this kind of problem on which work has already been done, the flat plate in forced convection may be mentioned. Instead of simply assuming a constant temperature or a constant heat-transfer rate, the conduction in a plate with specified properties is treated simultaneously with the convection process. Such problems have been called "conjugate" problems. Conjugate problems become particularly intriguing when several transfer mechanisms are at play, as for instance heat and mass transfer.

(c) The study on free convection caused by forces other than gravity, for example, accelerations due to vibrations and surface tension.

(d) Continued study of turbulent flow and turbulent exchange processes. From statements made at the Round Table Session, this research may be in a particularly exciting phase. The approach based on the introduction of model relations has already made it possible to analyze certain flows. There is a definite expectation that further advances will make it possible to predict the characteristics of turbulent flow in an increasing number of engineering applications. A second approach views turbulence as the occurrence of large-scale patterns random in nature, but persisting for relatively long durations. Those pursuing these investigations also expect to be able to offer design information in the not too distant future.

The possible fundamental topics on which fruitful work may be done are, of course, not exhausted by the above list. It simply represents some of those uppermost in the minds of the experts who contributed to the present survey. The listing of certain problems as "basic" is somewhat arbitrary, and it would certainly be justified to use this label also for many of the problems listed in the other sections.

(C) GENERAL VIEWS

In the discussion at the Round Table Session in Tokyo as well as in the correspondence prior to that session, two general topics were raised repeatedly. One of these topics concerned the funding of fundamental research and the other the communication of research results. Even though these topics are non-technical in nature, they do have a very major effect on the course of research and must be considered to be of prime importance.

1. *Fundamental research*

Serious concern was expressed by experts from several countries about the fact that it has become increasingly difficult to obtain funding for fundamental research. The funds that are intended for research are preferentially channeled into short-term development projects, with the expectation that design information will be provided within a relatively short time, say a year or so. Research conducted on this basis is frequently inefficient and often contributes little "basic" information, that is information of a kind that could be used in the solution of a broad range of problems.

It was also indicated that the report "Heat Transfer in the Seventies" might have contributed to this adverse trend. It is true that that report did list many applications. Such a listing, however, did not imply, and should not be interpreted to imply, any preference for short-range development projects over fundamental long-range research. The discussion of applications is essential because engineering research is based on problems which arise in connection with applications. The research problem then has to be formulated so that the phenomenon may be studied in detail. A successful project will then yield results that will benefit a number of different applications and not only the specific one which gave rise to the project. The study of turbulence provides a good illustration. It certainly represents a fundamental research problem which has been attacked by the most sophisticated and advanced methods. Yet the problem arose from the engineering need to predict friction and heat transfer in fluid flow, and the eventual results are intended to make such predictions possible thereby reducing expensive experimentation.

Actually when discussing the merits of long-range fundamental research over short-term developments with representatives of the sponsoring agencies, there is generally good agreement that the pursuit of basic work would be the most effective way of developing new knowledge. Nevertheless, the conditions and restrictions imposed on the available funds most often do not permit continued funding of long-range investigations into basic phenomena.

In order to improve this condition it will be necessary to make a more concentrated effort to explain the advantages of sustained funding of research. Perhaps this subject of financial support should be discussed more openly and perhaps it should be included as a topic at technical conferences even though it is not a technical subject in itself, and even though it is a little embarrassing to have to talk about money, let alone the lack of money.

2. *Communication of research results*

Engineering research in general and heat transfer research in particular is being conducted with the ultimate purpose of benefiting an actual application. Therefore, it is necessary to present the eventual results of heat transfer research in a form which is conveniently usable by the design engineer. In addition, information developed in the intermediate stages of research should be made available so that it may be easily reviewed by other workers in the field. The task of communicating research results, simple as it may be in principle, has become increasingly difficult, largely because of the wealth of important information that has been produced through research in the last several decades. Even though an enormous number of papers have been written and even though many survey articles, reviews, and handbooks have been prepared, the available data are generally not easily accessible. As a consequence we do not receive the full benefit of the tremendous research effort which has already been accomplished; many engineering projects proceed without the guidance from pertinent existing data, and a considerable amount of unnecessary duplication of effort takes place.

Much of this inefficiency could be avoided if a universal heat-transfer reference source could be developed. The desired source should be complete, it should be up to date, it should only contain information which has been critically evaluated by experts, and it should present the information in as convenient a form as possible.

To develop such a source several processing steps would be involved. First the literature would have to be reviewed systematically; the individual papers would have to be critically evaluated; next the pertinent results from several papers would have to be combined, and finally, the entire body of information would have to be published in such a way that the user could gain access to it quickly and conveniently. The necessary steps clearly require a major effort and they will have to be performed by very competent individuals. One cannot expect that this kind of effort will be forthcoming without appropriate incentives. At present there is no adequate system of rewards—be it by recognition or by financial compensation—that would encourage highly qualified persons to devote the necessary time to such a task.

At least, however, there is now a definite awareness of the need for such a source of information, and this fact is enouraging. To accomplish the task broad sponsorship will be needed and the thought was expressed that the lead may be taken by such organizations as UNESCO, The National Academy of Science, and the International Center of Heat and Mass Transfer.

Acknowledgement—This report is based on the advice and on recommendations obtained from a great number of experts in special fields of heat transfer. The report could not have been written without their generous and conscientious assistance. It is with sincere gratitude that the author wishes to acknowledge his appreciation for their support. Special thanks is due to those whose comments were used most directly in the preparation of this report, and their names are listed subsequently:

N. Afgan	A. Ramachandran
K. Bell	F. Reale
D. Benenson	V. M. K. Sastri
J. G. Collier	R. J. Simoneau
H. W. Emmons	D. B. Spalding
L. S. Fletcher	K. Stephan
P. Githinji	W. E. Stewart
J. P. Hartnett	J. E. Sunderland
L. S. G. Kovasnay	W. A. Sutherland
A. V. Luikov	D. K. Sze
B. Mikic	J. Taborek
B. Marcus	L. S. Tong
E. Pfender	

REFERENCES

1. R. H. Sabersky, Heat transfer in the Seventies, *Int. J. Heat Mass Transfer* **14**, 1927 (1971).
2. Round Table Session RT-3, Heat transfer in the Seventies, *Proc. 5th Int. Heat Transfer Conf., Tokyo*, 1974, Vol. 7, Japan Society of Mechanical Engineers, Tokyo (1974).