

# **PROCESS, ENHANCED, AND MULTIPHASE HEAT TRANSFER**

**A Festschrift for A. E. Bergles**

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**Process, Enhanced, and Multiphase Heat Transfer:**  
**A Festschrift for A. E. Bergles**

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## PREFACE

This festschrift volume is a compilation of all papers presented at the Arthur E. Bergles Symposium held at the Georgia Institute of Technology in Atlanta, Georgia on November 16, 1996. The papers included in this volume span the areas of heat transfer where Professor Bergles has made seminal contributions—heat transfer enhancement, pool and forced convective boiling, cooling of electronic and micro-electronic devices, single phase forced convection and process heat transfer. We gratefully acknowledge the contributions of all of the authors, most of whom are internationally recognized experts in their respective fields. The high technical quality and timely publication of this monograph owes much to the efforts of these contributors.

In the conceptualization, initiation and organization of this symposium, Professors Avram Bar-Cohen and Michael K. Jensen played a pivotal role. The success of this endeavor, including the organization of the various professional and social activities at the Georgia Institute of Technology, was, in large part, due to the efforts, encouragement and support of these two members of the organizing committee. Moreover, the assistance of Ms. Liz Schoonmaker at the Rensselaer Polytechnic Institute and Ms. Jessica Gordon at the Georgia Institute of Technology who provided valuable assistance in the organization of this event and Jim Allen who helped with the word processing nittie-gritties necessary for the production of this compendium is gratefully acknowledged.

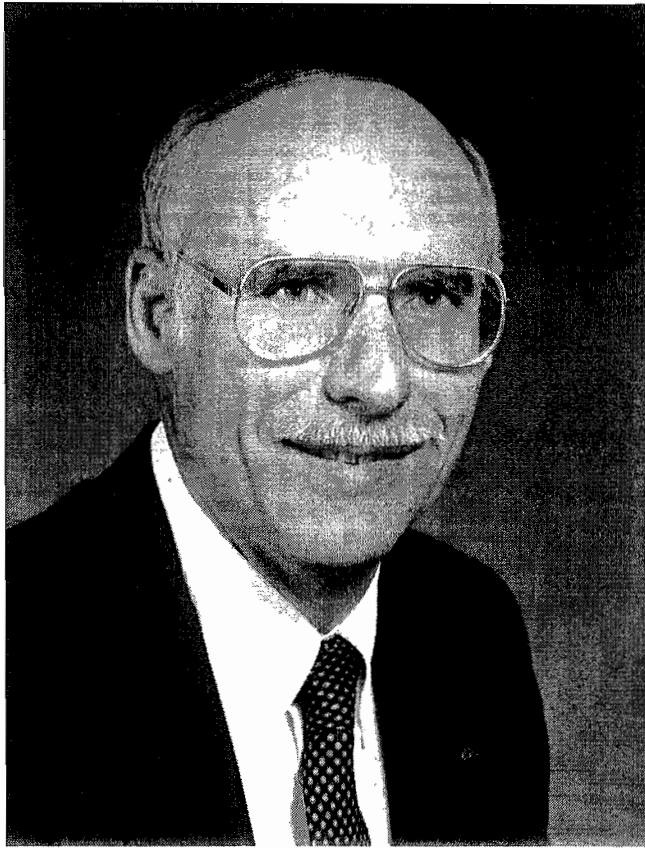
There are many colleagues and friends whose support, guidance and encouragement have played a key role in the publication of this festschrift volume. Because it would be difficult to thank each and every one of them individually, we would like to express our heartfelt thanks to all of them.

Finally, we owe much to the inspiration provided by Professor Bergles through his long, dedicated and illustrious career. His extensive and exemplary contributions to the field of heat transfer, engineering practice and education are in the finest traditions of innovation, research and application. We are thankful for all he has done and for his continued interest and leadership in the encouragement of new generations to extend this rich scientific tradition and heritage. Indeed, we have been privileged to be a part of this festschrift effort.

R.M. MANGLIK  
A. D. KRAUS



**ARTHUR. E. BERGLES**



## ARTHUR E. BERGLES

Professor Arthur E. Bergles has been one of the foremost articulators of the need for careful experimentation, appropriate numerical computing, and frequent interactions among various constituencies to achieve progress in the field of heat transfer. Indeed, drawing from the antecedents of pioneers in thermo-fluid sciences, for meeting the objectives of current research and practice, he has noted that “experimentation is necessary to resolve the complex problems that are encountered” [Bergles (1990a)]. Nevertheless, recognizing the increasing power and usage of computers, and their sophisticated application to complex problems, he continued “progress will depend on an expansion of capability in both experimentation and computation as well as synergistic interaction among practitioners in both arenas” [Bergles (1990a)] and among developers of information and users of information. Thus, his professional activities address fundamentals and practice, development and technology transfer, and education and training.

Born in Rhinebeck, New York on August 9, 1935, Arthur E. Bergles received his SB and SM degrees in 1958 and his Ph.D in 1962, all in mechanical engineering from MIT. He began his university career as a professor at the Massachusetts Institute of Technology (1963–1970), continued in this role at the Georgia Institute of Technology (1970–1972), at the Iowa State University (1972–1986), where he was Anson Marston Distinguished Professor of Engineering and department chair and at the Rensselaer Polytechnic Institute, where he has served as Dean of Engineering and is the Clark and Crossan Professor of Engineering. In addition, he has been a visiting professor at the University of Hannover and the Danish Technical University, and was Academic Guest at Lodz Technical University.

Art Bergles has earned numerous awards and honors for his professional contributions. He was elected to the National Academy of Engineering in 1992, and he is a Fellow of the ASME (1979), ASEE (1985), AAAS (1988), and ASHRAE (1992). Furthermore, his honors include the Alexander Von Humboldt Award (1979), ASME’s Dedicated Service Award (1984), SAE’s Ralph R. Teetor Educational Award (1984), ASEE’s Benjamin Garver Lamme Medal (1987), the AIChE Donald Q. Kern Award (1990), the ASEE Centennial Certificate and Medallion (1993), and the ASME-AIChE Max Jacob Memorial Award (1995). Some of his other recognitions are Purdue University Hawkins Memorial Lecturer (1986), Foreign Member of the Polish Society of Theoretical and Applied Mechanics (1987), 50th Anniversary Award of the ASME Heat Transfer Division (1988), Fellowship Award of the International Center for Heat and Mass Transfer (1988), and Honorary Member of the Union of

Mechanical and Electrical Engineers and Technicians of Yugoslavia (1993). In 1996, he was elevated to the ASME grade of honorary membership which is ASME's highest grade of membership.

Professor Bergles is or has been an editor or on the editorial board of *Journal of Heat Transfer*, *International Journal of Heat and Mass Transfer*, *International Communications in Heat and Mass Transfer*, *Experimental Thermal and Fluid Science*, *Journal of Enhanced Heat Transfer*, *Heat Transfer Engineering*, *HVAC&R Research*, *Applied Mechanics Reviews*, *Heat Transfer-Japanese Research*, *Heat Transfer-Soviet Research*, *International Series in Heat Mass Transfer*, *Bulletin of the International Center for Heat and Mass Transfer*, *Journal of Engineering Physics*, *International Journal of Heat and Technology*, *European Journal of Mechanical Engineering*, *Journal of Thermal Science*, *Latin American Journal of Heat and Mass Transfer*, *Latin American Applied Research*, and *Springer Mechanical Engineering Series*. His contributions to the archival literature include more than 300 published papers, and over 20 books or edited volumes. In addition, he has lectured in or organized over 40 short courses for universities, professional organizations, and industries and has helped organize numerous international meetings. He has presented over 280 invited lectures and speeches at U.S. and foreign universities, industrial organizations and professional societies.

Arthur Bergles' research has spanned the field of convective and ebullient heat transfer. His publications cover single- and two-phase flows in a variety of flow configurations, regimes, and applications. While Art and his students have performed some numerical and analytical studies, most of his work has been directed toward experimental investigations. One of his major strengths is the ability to extract and deduce from experimental data the physics governing a process. This insight has provided the starting point for other researchers to investigate the process farther. A detailed review of Art's wide-ranging contributions to the field is not possible in this short summary (an extended discussion is provided in the article by Professor S. G. Kandlikar). However, two areas of heat transfer in which he has made very significant contributions can be pointed out. These are in enhanced heat transfer and electronics cooling. Art has played a pivotal role in both fields.

Professor Bergles produced the first large review of enhanced heat transfer and developed the taxonomy for the classification of the various enhancement techniques. For the evaluation and use of these techniques, he has performed numerous fundamental and applied studies and he has relentlessly pushed for the adoption of enhancement technologies by the industry. As a result of this effort over the past

three decades, work in “heat transfer enhancement has grown at a rapid rate to the point where it can be regarded as a major field of endeavor, *a second-generation heat transfer technology*,” [Bergles (1988a)] with many new and exciting developments reported in the literature. However, “of greatest significance perhaps is the extent to which the more effective and feasible techniques are graduating from the laboratory to full scale industrial equipment” [Bergles (1988b)]. In fact, Art truly has defined the field of enhanced heat transfer and his philosophical focus on this important subject is perhaps articulated by the logo used in the Heat Transfer Laboratory

*wherever there is a  $\Delta t$  . . . . .*



**Heat Transfer Laboratory**  
**Rensselaer Polytechnic Institute**

at the Rensselaer Polytechnic Institute.

Furthermore, he was one of the first researchers to become involved in electronics cooling. His foresight was remarkable, as it is now recognized that many of the electronic devices/computers we take for granted could not operate as designed without significant cooling. This is reflected, for example, in his observation that “thermal problems [in electronics cooling] are so pervasive that they are spotlighted” and “research and development will be increasingly important to provide adequate thermal control for future microelectronic devices of extremely small scale” [Bergles (1990b)]. His leadership in this field is credited not only to his research accomplishments, but also to his interactions with industry.

Through his work, Art has always emphasized the applied aspects of fundamental research. He has strived to discover why something occurred, but at the same time he has endeavored to show how the results ultimately might be applied in industry. This balance in his work is continuing evidence of his desire to encourage more and better interactions between researchers and universities on the one hand, and designers and industrial organizations on the other. He recognizes the need for this cooperation for the betterment of the U.S.A., and the larger global community.

Professor Bergles’ career has been spent in universities. During this time he has supervised over 88 PhD dissertations, MS theses and research reports. A list of his students is provided herein at the end of this brief biography. He has always balanced the need to educate and train his graduate students with the demands of the research

project. He would push them to achieve more and to delve deeper into the process or phenomena under study, while at the same time he would engage in extended discussions and explanations so that the students could grow professionally. This educational approach is evident not only in his research, but also in the many courses he teaches to both undergraduate and graduate students; his lectures are always well prepared with clear explanations of major points, and they reflect his keen desire to pass on his knowledge. Art's commitment to education extends beyond the classroom through the many short courses he has offered to industry, professional societies, and universities.

In the area of leadership and service to the field of heat transfer few can match Art's accomplishments. He has been active on numerous committees of the ASME, AIChE, ASHRAE, ASEE, and other professional organizations. He has been chair of the ASME Heat Transfer Division, a representative to the Assembly for International Heat Transfer, and chair of the NSF Advisory Committee for Chemical, Biochemical, and Thermal Engineering, among others. He was chosen to be the chair of the U.S. study group to develop a cooperative program in heat and mass transfer with the former U.S.S.R. He is the current chairman of the International Center for Heat and Mass Transfer. His leadership has extended beyond the heat transfer field, as evidenced by his activities in the ASME (president of the society in 1990-1991, member of the Board of Governors, and other offices), and membership of the NSF Advisory Committee for Engineering. He has been tireless in the giving of his time and efforts to advance the field of heat transfer, and of engineering in general.

Because of his numerous research and service activities, Art is recognized worldwide as a leader in the field. His recent election to the National Academy of Engineering and elevation to Honorary Member of ASME are tributes to the high regard felt for Art by his many colleagues and friends. This esteem is not just based on his technical achievements, but also on the manner in which he has conducted himself throughout these years. He is patient, encouraging and supportive, has a calm demeanor, and is a thorough gentleman at all times. This has won him many friends around the world. On behalf of these friends and colleagues, we wish him well.

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# GRADUATE STUDENTS OF A. E. BERGLES

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Bakhru, N.	MechE
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Brown Jr., W. T.	PhD
Daleas, R.	NucE
Deane IV, C. W.	SB
Dina, J. L.	SM
Dormer Jr., T.	SM
Evans, R. G.	ScD
Fiori, M. P.	SM, NucE, PhD
Fuller, W. D.	SM
Gouda, S. C.	SM
Kelly, J. T.	SM
Lee, R. A.	SM
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Murphy, R. W.	PhD
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Pinto, C. G.	SM
Scarola, L. S.	SM
Shires Jr., J. W.	SM
Simonds, R. R.	SM
Skinner, B. C.	SM, NavalE
Snider, W. D.	SM
Thompson Jr., W. G.	SM
Vasilakis, A. D.	SM
Wessel, H. L.	SB
Yadigaroglu, G.	ScD

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Cooper, P. E.	MS
Kirkpatrick, C.S.	MS

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Bhavnani, S. H.	PhD
Bradfield, M. D.	MS
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Bunn, R.	PhD
Chyu, M. C.	MS, PhD
Hong, F. S.	PhD
Jensen, M. K.	MS, PhD
Joshi, S. D.	PhD
Khanpara, J. C.	PhD
Kim, C. J.	MS
Luu, M.	PhD
Manglik, R. M.	MS
Morcos, S. M.	PhD
Nair, R. K.	
Nirmalan, V.	PhD
Park, K. A.	PhD
Ravigururajan, T. S.	PhD
Reid, R. S.	MS
Royal, J. H.	PhD
Schlager, L. M.	PhD
Ziegler, R. P.	MS



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Champagne, P.	MS(Exp.)
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Jung, C.	Dipl. TUM
Lang, S. K.	MS, Phd(Exp.)
MacBain, S. M.	MS
Manglik, R. M.	PhD
Manwell, S. P.	MS
Oh, S. Y.	Phd(Exp.)
Pabisz Jr., R. A.	MS
Trewin, R. R.	PhD
Vandervort, C. L.	PhD
Willett, F. T.	Phd(Exp.)
Zitz, J. A.	MS

## hte interviews



*Since the interview printed here took place, Art Bergles has not slowed down in his pace of ever-increasing activities. His busy schedule has him working hard on all his projects at Iowa State University, AIChE, and ASME. He is currently planning a trip to China; unfortunately for all his numerous commitments it will be a jet flight rather than the proverbial "slow boat."*

**William Begell:** Art, I believe that this is a very good time to interview you for *Heat Transfer Engineering*. You have just finished your term as Chairman of the Executive Committee of the Heat Transfer Division of ASME, your term as U.S. (AIChE) Representative to the Assembly for International Heat Transfer Conferences, and your term as Chairman of the Department of Mechanical Engineering at Iowa State University. With the experience of having run a department and having been involved with heat transfer administration for a number of years, you have both a perspective backward and I am sure an interesting perspective forward, which we hope to learn more about today.

**Arthur Bergles:** Yes, after 11 years as department chairman and 5 years on executive committee assignments for both societies, it is an interesting time in my life. As far as the ISU administrative responsibilities go, I simply have one fewer full-time job. I am fully confident that other activities will expand to fill the time available. I look forward to putting more effort into research and teaching at the university and devoting more time to other ASME commitments.

### *Professional Short Courses*

**WB:** You have just started your second term as the Vice President for Professional Development of ASME, and I am sure that you have been concerned with heat transfer as well as with other areas of mechanical engineering. Your activities in planning short courses will obviously be directed toward all areas of professional engineering development. I am sure that you will have in mind the interests of the heat transfer community,

even though a job like the vice presidency requires you to be evenhanded.

**AB:** The Heat Transfer Division was an originator of the ASME short courses and has remained a strong participant in the national short course programs since 1976. One of the difficulties we have encountered is with the so-called high technology short courses such as heat transfer. These courses do not attract, on the average, a sufficient number of attendees to make them financially viable. Heat transfer, fluids engineering, and gas turbine courses are, in effect, subsidized by the well-attended programs in codes and standards. Perhaps we must regard the advanced level courses as being primarily in the area of service to the membership and the profession. Certainly, these courses are another way to disseminate technical information.

**WB:** I know that AIChE has a very extensive program of professional development short courses, probably much larger than ASME's. Is AIChE also experiencing the same attendance difficulties these days as is ASME?

**AB:** It is my understanding that the AIChE Today Series has experienced sharply reduced attendance recently and the number of offerings has been reduced accordingly. This is typical of short course programs around the country. Of course, there are some topics that have attracted much interest, for instance, computers, computer-aided manufacturing, and robotics.

**WB:** It seems to me that industries should "take advantage" of lulls in their operating level and support their engineering staff to increase their knowledge during those times so that they can cope with future competition and progress. History has shown that inevitably an upturn will come. A company that plans for the longer term would encourage this practice during the downturn and then would be prepared to face competition in the level of technology when the business cycle improves. I am sure that many chief operating officers of many companies have thought about such ideas long and hard, but that pressures from stockholders and fiscal people are overwhelmingly against such action. Do you agree with me?

**AB:** Most certainly. This is the kind of forward thinking that has to go on so that when the upturn does occur, that particular industry will

be in the lead. We found, however, that there is great resistance to supporting attendance at professional development programs. This is due not only to the time involvement, but also to the increasingly large travel and living expenses associated with a course that is given at a central location. In lieu of that, our most successful programs recently have been so-called in-house programs where the instructor comes to the organization. More employees can attend and the presentation can be tuned to the particular needs of the firm. We see further expansion in this area.

### *Effect of High Technology*

WB: In terms of high technology, specifically its relationship to heat transfer, what do you believe affects our profession most, the computer being the obvious starting point? Is there any new technology that you think will become very important that is looming over on, or on this side of the horizon in terms of instrumentation or techniques or whatever?

AB: I think we are finding that heat transfer is in the forefront of technology in terms of the analytical and experimental tools that we use as well as the products and processes that require the information. It has all happened very quickly. I did my master's thesis at MIT, using the Whirlwind Computer to solve a problem that could now be handled by a modest hand-held calculator. The computer is now routinely used by researchers and the applications personnel who rate and size heat exchangers. We will find that the techniques used in experimental research will increase in sophistication. This comment applies to computational heat transfer as well, since computer experiments must be run to test turbulence models and verify numerical schemes. Physical experimentation, I feel, will remain a very strong part of the research process. It seems that fewer research students are electing, or are offered, experimental studies of heat transfer phenomena. There is a tendency to select a numerical study where there is a greater probability of success in a shorter period of time than the physical experiments where all of Murphy's laws seem to still be in force. In my opinion, Eph Sparrow is an outstanding exception, as he can keep several dozen research students excited about their experiments in heat or mass transfer. We should note, however, that those

entering the experimental arena may not have very sophisticated tools given the deteriorating condition of academic laboratories. Even if the equipment can be purchased, resources may not be available to operate and maintain it.

WB: I detect in what you say, not only a prediction of the future, but also a tinge of nostalgia for the old data acquisition system, which included a pad of paper and pencil, rather than the automatic plotters of today, for writing down to the  $n$ th decimal point the readout of a potentiometer or whatever instrument was available at the time, and K + E graph paper. I was listening to what you said about the analytical versus experimental areas of study. In this respect, I would like to mention a recent issue of *Mechanical Engineering*, which was devoted totally to heat transfer and which was put together under your editorship. It was a wonderful collection of papers that you were able to assemble, particularly in the area of numerical versus analytical methods. Included was a very interesting article by Dick Pletcher and Suhas Patankar. I read this article with great interest, which mentioned some of the things that you were telling me now. Can you comment on trends a little bit more?

### *Teaching Real-World Applications*

AB: Perhaps I can editorialize further, since my good friends Dick and Suhas cannot provide a rejoinder. We will always have the temptation to extend the computer to situations where we have very little experimental evidence, thus running the risk of not having the base points to make sure that the computation scheme is accurate, that there are no bugs in the program, etc. The computer is an enormously powerful tool for extending our understanding and predictive capability, but we must always have some means of checking the calculations. Of course, as the situations that we consider become more complicated, the experiments themselves may be subject to errors. I have encountered numerous situations where the numerical algorithms or simply the program itself contained errors, which were detected by comparison with experimental data.

WB: You seem to be saying that essentially nothing beats hands-on experience. Old-time engineers can design a shell-and-tube heat exchanger and

come out with a certain length of tube or a certain number of tubes or a tube diameter that they know is wrong because it doesn't jibe with what is successfully operating in the field. On the other hand, I hear many engineers today, including young computer-oriented individuals, say that they simply take the answer from the printout and have no feel whether the answer is correct or not. In our field of heat transfer we are faced with the necessity of combining very, very high technology with very basic hands-on experience. This is an irreplaceable combination and I think it is great. But I believe, and I want you to comment on this idea, that it is up to teachers like

security, in part due to all of the digits that are displayed. Eight significant figures are not very useful when the answer is only good to within plus or minus 50% anyway. An order-of-magnitude sense is vital to detect programming and keying errors. We must instill in our students an appreciation of whether the heat transfer coefficient is 1, 10, 100, or 1000 so that they can come up with an intelligent appraisal of a rating or design problem.

WB: That was a nice summary, ending with a list of heat transfer coefficients going from 1 to 1000. Now this increase in heat transfer coeffi-

**"We hope to continue . . . to bring order into this new discipline of heat transfer and reduce some of the entropy generation inherent in heat transfer communications."**

yourself to instill the ability to judge the correctness of an answer in our young engineers who will be running our industry in the years to come.

AB: I fully agree with you, and the place to start, of course, is with the undergraduate heat transfer course. We should certainly introduce the computer, at least in an illustrative sense, for solving certain problems, particularly in conduction. But we should also bring into the classroom the hands-on experience or take the students down into the lab and let them see and touch heat exchangers and really get an appreciation of the real world of hardware. Too often, we spend our lecture time going through boundary layer theory and find that we are too short on hours to discuss applications or to have a laboratory experience. I would hope that we can reverse this trend because we have found that most of our undergraduates are going to be confronted with the hardware problem, one way or another, and the necessity to solve practical problems. Toward that end, I firmly believe that the young engineer's best tool will be the ability to do back-of-the-envelope calculations such that they can get reasonable approximations to heat transfer coefficients and other necessary parameters. Above all, they must be able to recognize the order of magnitude of the answer. The computer and the powerful hand-held calculator, for all of the benefits that they have brought to us, have given almost a whole generation of students a false sense of

coefficients is probably the thing for which Art Bergles is best known—I speak here of heat transfer augmentation. I think it would be amiss not to talk to you about heat transfer augmentation and two-phase heat transfer in this interview. Can you tell me about your plans for pursuing your work in these two areas, now that you have more time available?

***Heat Transfer Augmentation***

AB: I have been very privileged to work in two of the most exciting areas in heat transfer. I began with two-phase flow and heat transfer when I worked with Joseph Kaye of MIT on the cooling of electronic and electrical equipment. The project I embarked on for my dissertation was the cooling of high-field magnets, an area that was in the late 1950s of particular concern to solid state research at the MIT National Magnet Laboratory. Unfortunately, Professor Kaye passed away early in my doctoral program. I then had the good fortune of becoming associated with Professor Warren Rohsenow who became my mentor in boiling heat transfer. After I spent a year on the research staff of the Magnet Laboratory, Warren gave me the opportunity to return to the mechanical engineering department as a faculty member. Since 1963, I have been associated with the teaching of mechanical engineering with emphasis

*(continued on page 141)*

on heat transfer. Now, boiling is a very high heat transfer coefficient situation. Yet, when I first started work in the area, I attempted to obtain the very highest heat fluxes by fair means or foul, in particular, to elevate the critical or burnout heat flux, with immediate application to the high field electromagnets. This naturally led to the consideration of the diverse means whereby the critical heat fluxes might be augmented or enhanced, and expanded into many other situations which do require heat transfer coefficients higher than those obtainable under normal conditions. The work subsequently included enhancement of free convection, that is, some four orders of magnitude lower heat transfer coefficient than in boiling. We could say that from the very beginning, I have been quite sensitized to the problem of the order of magnitude of heat transfer coefficients.

WB: Art, as I said before, you will have more time for active research now that you have given up so many of your administrative duties, not all by any means, but a lot of them. What is your plan for future research and concentration of your interests? Are you still going to continue in the area of boiling and high heat fluxes and enhancement or do you have other areas in mind?

#### *Database Publication*

AB: I will very definitely continue in the area of enhanced heat transfer or second generation heat transfer technology. Since establishing a heat transfer laboratory at Iowa State in 1972, I have had a very extensive ongoing program of work in enhanced heat transfer ranging from free convection to forced convection boiling. In addition to many studies of the phenomena and mechanisms, we have developed a database of literature in this area. We scan the heat transfer literature on enhancement that appears worldwide, classify it, then disseminate the information to the community. That literature has experienced an exponential growth, and we are presently logging in over 300 papers per year. We hope to continue this effort to bring order into this new discipline of heat transfer and reduce some of the entropy generation inherent in heat transfer communications. Along with the research projects, now

about ten, and the documentation, I have returned to a long-standing project to complete a reference book on the subject with my friend and colleague, Ralph Webb. I believe that the necessary time will now be available to finish that project.

WB: That, of course, is music to my ears as the publisher of that book. The database of enhancement literature that you mentioned has been partially published and is available to the community in, I believe, *Previews of Heat Transfer*. I would direct all readers of *Heat Transfer Engineering* to that publication to look up the literature there, which has been cited up to what year?

AB: That collection of literature, which was presented in six installments from 1978 to 1980, included about 1500 references. Our newest edition of this literature search will contain over 3000 references. Needless to say, we have been employing the computer for many years to assist with the task of organizing and retrieving the literature.

WB: Will you or your university make the database printout available to people who are interested or have you considered putting it into a commercial database so people can obtain it for a commercial fee?

AB: The database is readily available through our reports, which for the past 5 years have been sponsored by the Department of Energy. It is not clear whether the sponsorship will continue, but we do hope to continue the project. It would be a shame to stop after having kept up the literature acquisition for 20 years.

WB: I would like to urge our readers of *Heat Transfer Engineering*, especially all those who are interested in enhanced or augmented heat transfer phenomena, to get in touch with Professor Bergles at Iowa State to obtain copies of this latest addition to the literature. Turning to another subject, could you comment on the status of the agreement for scientific exchange with the Soviet Union in the area of heat and mass transfer?

#### *International Collaboration*

AB: I have always felt that international collaboration is vital if we are to carry forward meaningful heat transfer research and engineering and that

this collaboration should be done on an organized basis with the full agreement of the governments of the participating countries to be fully effective. In 1979, I was appointed by President Carter to head up the U.S. side of a program in heat and mass transfer under the U.S./USSR Agreement in Science and Technology. A major meeting was held in Moscow and Minsk later that year to define the protocol for collaboration as well as the areas of immediate interest for cooperative research. We felt that this meeting laid the groundwork for the formal cooperation between our two countries. Of course, on a person-to-person basis there already existed collaboration in a number of areas. At the end of 1979, world events took over. As a result of the continued intensification of the political situation, when the S & T agreement expired July 7, 1982, it was not renewed. Hence, I no longer hold that chairmanship. But I do hope that the individual collaboration will continue on a meaningful technical and personal basis so that we as engineers can contribute to the lessening of current tensions. When I met my Soviet counterpart in this program, Professor Styrikovich, at the International Heat Transfer Conference in Munich last fall, he and his colleagues made the offer that they would like to continue, on an informal basis, collaboration that would be of mutual benefit to interested parties. It would, of course, be on the traditional receiving-side-pays basis, an arrangement that is much easier for our colleagues in the Soviet Union to carry out than it is for us. Nevertheless, that offer has been made and would be, I think, of interest to a number of the U.S. researchers.

### *Sabbatical in Germany*

WB: Well, politics is probably more unpredictable than any mode of heat transfer. Even though relations between the Soviet Union and the U.S. are currently tense, I certainly hope that an agreement in our area of interest will be reached as soon as the relations get better. In the meantime, the opportunity for individual contacts is continuing at various international forums such as the meetings, seminars, and summer schools of the International Centre for Heat and Mass Transfer in Yugoslavia. This brings me to European travel and the fact that you have recently returned from a sabbatical with Professor Mayinger

in Hannover. Are you looking forward to the next one in about 5 years hence?

AB: Yes, I did go to Germany in 1979-1980 for my first sabbatical ever, joining Franz Mayinger at the Institut für Verfahrenstechnik in Hannover. This renews an acquaintance that began some 21 years earlier at the Technische Hochschule, now Technische Universität, München, when Franz was completing his dissertation for Ernst Schmidt and I was a visiting graduate student of Professor Schmidt's as a holder of a Fulbright. It was a real pleasure to be with Franz Mayinger again, and, as fate would have it, he subsequently returned to Munich to assume the Chair that Grigull, Schmidt, and Nusselt once held.

WB: Your wife and children joined you in your European sabbatical. Are they longing to go back to Europe and urging you to accept another such arrangement when the time comes?

AB: We went at an optimum time in terms of the school years of the boys. As I look at our increasingly diverse schedules now, I think it would be quite difficult, if not impossible, to arrange a similar sabbatical and to derive the same pleasure that we had from that visit. To elaborate, my wife, Penny, has gone back to work. She is a programmer-analyst at the Iowa Department of Transportation, resuming in somewhat different form a vocation that she started in 1960 at the Instrumentation Laboratory, now Draper Laboratory, at MIT where she was working on the Apollo program. Our older boy, Eric, is now heading off to college at Colorado State and our younger son, Dwight, will be a sophomore in high school. Eric is a basketball player and is setting his sights on a career in business. Dwight is a swimmer and bicycle racer with early aspirations to be a marine biologist, a vocation that is not getting too much inspiration from the Iowa prairie.

WB: I know that you travel quite a lot. Every time I telephone, your secretary says, "Professor Bergles is out of town and will not be back until next Monday." With so much traveling, I am sure that you have made many contacts all over the world. I know that you frequently teach short courses with your colleagues from the U.K. and France. Are there any other international connections that you would like to tell us about?

AB: Well, through the years I have had the good fortune to be involved with collaborative programs with a number of countries in addition to the USSR and Germany. These include the long-standing program of NATO Advanced Study Institutes in Turkey, cooperative seminars with Japan, and an arrangement with Portugal. I am presently developing programs in Argentina, India, and the People's Republic of China. Not all of these involvements get me to these countries on a regular basis, but they have been technically significant and very rewarding personally.

WB: Switching to another subject, I know that one of your very, very deep interests is the background of heat transfer and where heat transfer came from, the historical aspects of heat transfer. It has been said that "today will be history tomorrow." Can you tell us more about your work and interest in the area of the history of heat transfer?

AB: The "roots" of heat transfer are more an avocation than an area in which I have done serious work, but I have prepared a few articles on the subject. I think it is very important, regardless of the scientific or technical specialty in which we work, to have a sense of history because past is indeed prologue. This is a particularly auspicious time for heat transfer as many significant anniversaries are appearing. We have passed just recently the 100th anniversary of Nusselt's birth. One

hundred years ago Reynolds published his pioneer study and we are approaching the 100th anniversary of Graetz's work on laminar flow. It is enlightening to go back in time and see how perceptive the early workers really were. The papers of 50-100 years ago often contain valuable "new" information in terms of ideas and insight into the various processes. I hope to bring a sense of this history to the heat transfer community in a modest way through the "Heat in History" column of this magazine. It seems to be increasingly important to do this since the burgeoning literature keeps all of us from having even a modest control over our own specialty literature that is appearing in real time. I believe that if we have this sense of history and if we do try through reviews and critical surveys to digest the current literature, we will much better control our destiny and future as to areas that we work on and the means whereby we explore the subject areas. All in all, I feel that there are enormous "existential pleasures" to be derived from heat transfer research, engineering, and education.

WB: In closing, I would like to say that I hope your professional and personal life and existential pleasures will be not only augmented, but also enhanced, every step of the way. Thank you very much for coming to talk to us today.



## 13 Years Later: An Interview with Art Bergles

The editors of this Festschrift for Art Bergles have approached me to conduct a follow-up interview with our honoree. The original interview was printed in *Heat Transfer Engineering* in 1983.

I caught up with Art in Houston, in August 1996, during the National Heat Transfer Conference and the interview below is the result of this meeting.

It is a great privilege and honor for me personally and for my publishing house to be involved in the presentation of this festive volume. I have been associated with Art Bergles for many many years and hold him and his family in great professional and personal esteem. I wish him many more years of fruitful and effortless endeavors and great success.

Bill Begell

**William Begell:** Art, the last interview with you was published in *Heat Transfer Engineering* 13 years ago. During this period there have been many accomplishments in your career. You served as President of ASME, you moved to Rensselaer Polytechnic Institute, you were the Dean of Engineering there. Please tell me about your professional happenings since 1983. I may have missed some.

**Art Bergles:** The past 13 years have indeed been a time of great change for me. Looking at the gainful employment first, I was able to relax a bit at Iowa State, as Anson Marston Distinguished Professor of Engineering and Professor-in-Charge of the Heat Transfer Laboratory. In 1986, however, we moved to Troy, New York, where I became the Clark and Crossan Professor of Engineering at Rensselaer Polytechnic Institute. This move was based on personal considerations as well as the outstanding professional opportunity of the endowed chair. My father died in 1985, and we were now only 70 miles away from the family property, in Rhinebeck, New York, where my mother lived alone. Also, our boys were away at college: Eric, finishing up at Colorado State, and Dwight, just starting at Boston University. In 1989 I became Dean of Engineering, serving in this capacity until 1992, when an emergency

hospitalization and operation nearly led to an end of my involvement in everything. Fortunately, I recovered motor functions to some extent, and have been able to engage in many of the old activities these past four years. Perhaps the foremost of these is the RPI Heat Transfer Laboratory, which I established in 1986, and which I have been the director. In the volunteer department, I was elected two times to the Board of Governors of ASME (1985–89) and was the 1990–91 President of ASME. The latter is a three-year commitment, as president nominee/elect, president, and past president. Needless to say, it was an extraordinary busy time.

I have done a few other things, too: Chair of the NSF Advisory Committee for Chemical, Biochemical, and Thermal Engineering; member of the NSF Advisory Committee for Engineering; and now Chair of the Executive Committee of the International Center for Heat and Mass Transfer. I'm on the editorial advisory boards of 17 international thermal science journals, some of which require a fair amount of work.

**WB:** If I recall correctly, the ASME Presidency was held by more members of the Heat Transfer Division than any other Division in the Society. Recall for us the Heat Transfer Division Presidents and explain this phenomenon. Are the heat transfer engineers most active, most able, most ambitious?

**AB:** Of the 115 ASME presidents, many have made heat transfer their technical specialty. Among the current groups of 20 ASME past presidents, Ernest L. Daman, Nancy D. Fitzroy, Leroy S. Fletcher, Richard J. Goldstein, Serge Gratch, Charles E. Jones, S. Peter Kezios, and myself are identified with heat transfer. This is probably more than our fair share, considering that there are now 37 boards or groups in the five ASME councils. While there are plenty of challenges in heat transfer, heat transfer specialists, in either academia or industry, have been unusually willing to work for professional societies. With persistence, and luck, some have made it to the top of ASME.

**WB:** Last time we spoke, we touched upon the computational aspects of heat transfer research ver-



sus the experimental techniques. With the help of hindsight, can you comment on what has transpired in our profession over the last decade and a half in terms of computing and experimentation.

**AB:** This is truly the age of the computer, in heat transfer as well as in engineering and science generally. Some conservation principle must be at work, for as computer technology has been adopted everywhere, there has been a widespread decline in laboratory work. This loss in classical experimental capability is especially detrimental to enhance heat transfer, my main field of endeavor. Even if computer simulations were effective for more than several of the 14 enhancement techniques, the actual experiments would be necessary to bench-mark the computer codes. Experimentation, as we have known it, appears to be a dying art. The concerns that I voiced in 1983 have been realized. Now, if you will excuse me while I get out my laptop to check the e-mail...

**WB:** What about the teaching of heat transfer today as compared with the early 1980s? Are heat transfer courses finding their way into non-mechanical, non-chemical, non-nuclear engineering courses like electrical, civil, etc?

**AB:** The teaching of heat transfer has eroded. It is a required course in fewer curricula, especially where heat transfer or unit operations is not central to the discipline. Due to the explosion of knowledge, disciplinary courses have pushed aside the thermal-fluid engineering sciences. One need only observe that heat transfer is no longer a required course in the undergraduate mechanical engineering program at M.I.T.! Heat transfer textbooks have grown larger, and the number of problems has increased. A complete solutions manual and computer disks appear to be necessary for a successful undergraduate textbook. In my recent experience, the student wants to be entertained and the instructor wishes to have as easy a time of it as possible. There seems to be less of the practical; heat exchange technology and design are not usually frequently covered in the basic course.

**WB:** Have you kept up your activities in heat transfer augmentation? How about two-phase flow?

**AB:** With the assistance of colleagues, and the aid of some excellent graduate students, I have kept up my activities in heat transfer augmentation or enhancement. This work is intertwined with two-phase flow and heat transfer. Major projects were carried out on single-phase heat transfer from internally finned ceramic tubes; single-phase flow in tubes with

twisted-tapes; boiling with enhanced tube bundles (flow through), critical heat flux in subcooled flow boiling – plain or enhanced with twisted tapes or additives to the water; boiling from enhanced, simulated microelectronic chips; and enhancement of refrigerant evaporators by micro-fin and deep-spirally-fluted tubes. I am closing out my research activities with studies of enhancement of power transformer oil coolers by addition of water spray, the effect of a micro-fin tube on heat transfer to an alternative refrigerant, enhanced heat transfer to the interior of simulated gas-turbine blades (rotating), and active enhancement in single-phase duct flow. For these studies, some of the largest and most complex experimental rigs I have worked with were constructed.

**WB:** You spoke about data-base publishing back in 1983. Now, with the advent of Internet, in particular, and electronic publishing, in general, we are facing a brave new world. How does heat transfer fare in cyberspace and in the information superhighway?

**AB:** We are indeed facing a “brave new world” in communicating heat transfer results. The internet will make available more data than any other technology in history — if we can access it. There is clearly an information overload, that is not alleviated by the computer. We recently assembled another citation data base on enhanced heat transfer (through mid-1995). In hard-copy form, it takes a 11/over 2-in.-thick report to document the 5676 citations. Of course, this information is nicely covered on two disks. A great deal of manual searching was necessary, because the existing search programs and alert journals do not sweep up all the literature. Manual searching was particularly relied upon when doing early versions of the report, especially since the first reference was published in 1861.

We are faced with a break in knowledge, newer research students will rely only on computerized data bases, and if a reference has not been entered into such a data base, it will not be cited or used. As a result, Santayana's prophecy is being borne out: “those who ignore history are condemned to repeat it.”

Of course, we can do some wonderful things now with desktop publishing. What concerns me is the quality of the dialog. People are concentrating more on how it is written rather than on what is said. Then, too, there is nearly instant communication, via fax, e-mail, and voice mail. Prompt communications are so ubiquitous that there is a tendency to clutter up cyberspace and overcrowd the electronic highway with unnecessary communications. In my view, we

are in danger of becoming roadkill on the electronic highway.

**WB:** Too many events happened on the international scene to be squeezed into the few columns of this conversation. The demise of the USSR, the falling apart of Yugoslavia, and the ensuing move of the International Center of Heat and Mass Transfer from Belgrade and Dubrovnik to Turkey. The adding of the word International to ASME. I am sure your thoughts and comments will be of great interest to us all.

**AB:** Fragmentation of nations and globalization is everywhere. As the world is broken into smaller pieces, there is a tendency for heat transfer to be splintered also. More truly international meetings are vital to the transport of information and furtherance of the art and science of heat transfer.

There must be help to restore the excellent capability for thermal research in the nations of the former Soviet Union and in the former Yugoslavia. The situation is particularly desperate in Bosnia-Herzegovina and Croatia. The difficulty, of course, is that Western institutions are being "reengineered," and funds for collaborations are in very short supply.

The competition has intensified, as thermal design and production of heat-exchange components can be done far away. This requires modern communications, but it does take advantage of lower-price technical labor. Survival is a real issue in many cases, and it is leading to cut throat practices in some areas of heat transfer. The place where I notice this most is in reviewing of papers. There is simply no time available for researchers to do the important volunteer work of paper reviewing, which, in essence, is the quality control for our publications.

**WB:** We started our 1983 interview speaking about the woes facing professional development resources. What has happened there? Now the problems we face are severest in the library budget area. Please tell us more.

**AB:** It seems that short courses are picking up, after a rather long downturn. Thermal sciences courses are again attracting interest; but "general interest" courses in manufacturing, mechatronics, etc., are "in" right now. There is much emphasis on "tools," such as finite-element analysis, and multimedia presentations. With the rapid downsizing of corporations, much experience and expertise is lost. Short courses, particularly if they are given "in-house," offer the chance to re-establish that knowledge in current employees.

Library budgets are under severe pressure, probably around the world. Books (any sort: textbooks, reference books, conference proceedings) are not being purchased, and journal subscriptions are being cut. Having located a reference, it may be difficult to obtain it — even through interlibrary loan. Electronic journals are touted as the solution, but there is a cost issue there, too. It is very frustrating for researchers to publish papers that are unavailable locally.

**WB:** Your children must now be all grownup. Tell us about your family and your plans for the future. What about travel?

**AB:** The boys left the "nest" some time ago. Eric graduated from Colorado State, and is market research specialist in Mountain View, California. Dwight graduated from Boston University and Stanford, and is doing a post-doctoral stint at the Vollum Institute, Oregon Health Sciences University. He and his wife, a lawyer, live in Portland, Oregon. We see them only several times a year.

Time has marched on, and I will retire in June 1997. This academic year, I am on "terminal" sabbatical, much of the time in Europe. For three months, I will be at the Technical University of Munich working with Franz Mayinger, with whom I had my only previous sabbatical at the University of Hanover. This is fitting, as I studied in Munich during 1958–59. Other visits are planned for Denmark, Italy, Poland, Portugal, Slovenia, and Switzerland.

Penny and I already have a retirement house in Centerville, Massachusetts, on Cape Cod. We'll do some traveling, of course, but there I can spend the time worrying about the heat transfer problems of fish and clams. Now there's an interesting problem: what keeps them from freezing during the winter?

## PLENARY LECTURE

# ARTWORK- A REVIEW OF RESEARCH WORK DONE BY PROFESSOR ARTHUR (Art) E. BERGLES

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## ABSTRACT

Professor Arthur E. Bergles has made major contributions in a number of areas in heat transfer. This paper presents a review of 300 papers published by him, and with his students and co-workers, through December 1996. Professor Bergles' research work can be broadly categorized into seven areas: (i) enhanced heat transfer, (ii) two-phase flow and heat transfer, (iii) heat transfer to refrigerants (boiling and condensation), (iv) cooling of electronic components, (v) laminar internal flow, (vi) review and general papers, and (vii) history of heat transfer. This research, conducted over more than 30 years, has produced a wealth of high-quality experimental data, theoretical models, and their practical applications. One of the major objectives of this article is to highlight these contributions and identify their sources, to facilitate future researchers and designers in developing new theoretical models and in designing industrial equipment.

## 1. INTRODUCTION

The research work of Professor Bergles conducted over a span of over thirty years is a great gift to the heat transfer research community in academia as well as in industry. Professor Bergles, through his extensive reports and publications, helped us all in defining the research needs through his visionary review papers, then identifying for industry the potential benefits of conducting fundamental and applied research work, especially in enhanced heat transfer, and finally as a true researcher to his soul, setting out to obtain invaluable experimental data as well as insight into the underlying mechanisms governing the related phenomena in numerous fundamental problems. It is the best gift to us all from Professor Bergles, that helped define many careers for many of us, and produced and improved many

products for the benefit of mankind.

The experiments conducted by Professor Bergles not only provide valuable data, but also bring out the importance of properly designing an experimental set-up to obtain the desired data by carefully controlling and limiting the influence of extraneous variables. The approach taken by Professor Bergles shows the thoroughness he applies in the design of the entire study covering a specific topic. As seen from his studies on twisted tapes, turbulators, microfins, and porous coatings, to name a few, he has first considered a list of alternatives, and then narrowed it down to specific configurations through broad experimental investigations. This was followed by conducting well thought-out experiments to reveal the most important parametric trends for the targeted configuration, an art he has displayed time and again. From these parametric studies, he has provided specific directions to the researchers in academia as well as in industry. The generosity that everyone has experienced while in his company is evident even in his research work through extensive survey papers written by him giving insights into the fundamental as well as applied aspects of numerous heat transfer related problems.

A list of research publications by Professor Bergles published through December 1996 is included under the list of references<sup>1</sup>. The papers are classified into ten categories as shown in Table 1. The numbers in front of a category indicate the paper reference numbers.

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<sup>1</sup> The list of references is in a slightly different format. Since there are many papers with the same authors in a given year of publication, the papers are numbered and are listed in a chronological order. The papers are referenced by these numbers in the table and the text (within square parenthesis).

**TABLE 1. PUBLICATIONS BY PROFESSOR ARTHUR. E. BERGLES IN DIFFERENT RESEARCH AREAS**

RESEARCH AREA	REFERENCES
Subcooled Boiling with Special Emphasis on Cooling of High-Flux Components	4, 5, 18, 25, 33, 43
Fundamental Studies in Enhanced Heat Transfer	6, 8, 10, 16, 17, 24, 30, 36, 40, 45, 47, 51, 53, 56, 59, 62, 64, 67, 76, 80, 85, 90, 91, 93, 99, 103, 104, 114, 115, 116, 117, 123, 127, 128, 130, 136, 138, 139, 145, 147, 148, 152, 155, 156, 157, 160, 161, 164, 165, 171, 172, 180, 181, 182, 191, 192, 193, 194, 196, 199, 205, 209, 212, 213, 214, 215, 222, 224, 225, 226, 228, 230, 231, 232, 233, 235, 236, 237, 238, 239, 246, 249, 250, 251, 252, 258, 261, 264, 265, 267, 268, 270, 273, 275, 277, 278, 279, 281, 282, 287, 288, 289, 290, 292
Fundamental Studies and Reviews of Two-phase flow and Heat Transfer	9, 11, 12, 15, 20, 21, 22, 26, 27, 28, 32, 39, 50, 60, 70, 72, 73, 79, 96, 97, 100, 107, 112, 126, 131, 135, 143, 144, 146, 166, 188, 195, 241, 248, 253, 254, 257, 259, 260, 263, 266, 269, 280, 283, 293, 294, 295
Instability of Two-phase Flows	7, 13, 29, 31, 37, 38, 42, 44, 46, 48, 54, 71, 98
Heat Transfer to Laminar Internal Flows	23, 34, 41, 57, 61, 65, 69, 83, 106, 108, 118, 119, 120, 125, 129, 198, 286, 298
Flow and Heat Transfer of Refrigerants (Including Evaporation and Condensation, pure and oil-refrigerant mixtures)	158, 159, 170, 175, 183, 185, 187, 192, 204, 206, 207, 208, 210, 242, 243, 271, 284 (papers on enhanced tubes covered under Fundamental Studies in Enhanced Heat Transfer)
Reviews of Enhanced Heat Transfer	19, 35, 49, 52, 66, 74, 78, 84, 86, 88, 89, 92, 94, 95, 101, 102, 105, 109, 110, 111, 113, 121, 122, 132, 133, 134, 137, 141, 142, 149, 151, 153, 154, 173, 189, 223, 229, 255, 276, 291, 296, 300
Studies and Reviews of Cooling of Electronic Components	68, 81, 82, 140, 150, 162, 163, 166, 167, 168, 174, 176, 177, 178, 200, 201, 202, 203, 218, 219, 220, 234, 245, 256, 262, 272, 274, 299
General Heat Transfer	1, 2, 3, 14, 55, 58, 63, 75, 87, 169, 184, 190, 197, 216, 217, 221, 227, 240, 244, 247, 285, 297
History of Heat Transfer	77, 124, 179, 186, 211

## 2. Review of Research in Specific Areas

Table 1 covers all the three hundred papers published by Professor Bergles. The following review presents the highlights and some important details and relevance of his work. Due to space constraints, all the paper listed in Table 1 could not be discussed. Although figures and tables are not included here, the readers can identify the relevant papers from the information presented here, and then refer to those papers to find additional details.

### 2.1 Enhanced Heat Transfer

Professor Bergles has been one of the most active proponents of enhanced surfaces in heat transfer applications. He has displayed a vision to recognize the importance of enhancement in refrigeration, power, process, and microelectronic cooling applications. In his 1979 paper on energy conservation via enhancement (Bergles et al. [93]),

he outlined the steps needed for developing enhanced surfaces for commercial applications. As stated in his paper, "Commercialization represents the ultimate stage of development; however, even commercial products require additional development work". He is among the first ones to comprehensively address issues related to the application of enhanced surfaces - fouling, manufacturing and development cost, and performance evaluation criteria for their selection. He undertook the task of identifying the underlying heat transfer and pressure drop mechanisms (for internal enhancement techniques) for these enhancement devices, and provided insight which led to further improvements. Vibration, ultrasonics, twisted tapes, bent-strip inserts, finned tubes, microfin tubes, microporous surfaces, microstructured surfaces, and stepped and wavy surfaces are among the enhancement techniques he investigated, providing a rich wealth of experimental data and a better understanding of the heat transfer mechanisms associated with these devices.

### **2.1.1 Single-phase enhancement**

**Vibration and Additives.** Mechanical vibrations effectively cause localized pressure fluctuations in the liquid adjacent to a heat transfer surface. When the liquid is close to its saturation temperature, enhancement is possible due to nucleation and collapse of bubbles. Professor Bergles became interested in this technique while working on the cooling of high-field electromagnets at the National Magnet Laboratory at MIT (Bergles [6]). To enhance the heat transfer to water flowing in the cooling channels, the channel walls were subjected to vibrations. The localized instantaneous reduction in pressure during a cycle resulted in cavitation in the water at the channel walls. For wall temperatures of about 30 °C below the saturation temperature, the single-phase heat transfer coefficient remained unaffected. However, as the wall temperature approached the saturation temperature, the heat transfer coefficient gradually increased, yielding up to 100 percent increase. The enhancement was reduced as fully developed boiling conditions were established at higher wall temperatures. The effect of ultrasonic vibrations was tested further (Bergles and Newell [8]) with water flowing in annuli. They provided experimental results in a parametric form to show the effect of system pressure, annulus dimensions, vibrational intensity and wall superheat. The presence of vapor in the flow channel drastically reduced the enhancement, indicating the applicability of this technique only to the subcooled region. The tubes were direct electrically heated in the experiments, a technique that Professor Bergles used extensively later with his in-tube research work to obtain local heat transfer data.

**Twisted tape and other inserts, and internally finned tubes.** Mechanical inserts and internal fins directly affect the fluid flow field and the associated heat transfer process. Twisted tapes and other in-tube inserts have been a major topic of Professor Bergles' research on enhanced heat transfer since 1969. In his first paper on this topic, he reported a detailed experimental study (Lopina and Bergles [16]) on heat transfer and pressure drop with twisted tape inserts with water in fully developed turbulent flow. The enhancement, as much as 100 percent, was attributed primarily to the increased flow path, the increased circulation, and the tape fin effect. An additive model was proposed to predict the heat transfer coefficient from these mechanisms. The contribution to heat transfer due to fin conduction was shown to be small, about 8 to 17 percent, for perfect contact between the tape and the wall. For a constant pumping power, twisted tape inserts provided a 20 percent improvement in heat transfer over an empty plain tube.

Surface roughness and twisted tapes both provide enhancement, although the mechanisms in the two cases are different. The effect of combining these two techniques was investigated (Bergles et al. [24]) in the turbulent region. Since the two mechanisms do not overlap, the combination was expected to provide further improvements, as was indeed the case. The superposition technique worked well for correlating the heat transfer data in spite of highly

non-linear nature of the mechanisms. This helped to clarify the discrepancies between two twisted tape data sets obtained with the same geometry - attributable to the differences in the surface roughness of the tubes.

The effect of brush and mesh type inserts was also studied experimentally (Megerlin et al. [53]) for high heat flux applications. Both inserts yielded dramatic improvements in heat transfer coefficient, up to 1000 percent increase, as compared to plain empty tubes. However, the pressure drop penalty was extremely high, up to twenty times higher in certain cases.

Internally finned tubes are another form of enhancement technique that were extensively tested by Professor Bergles (Bergles et al. [36]). The heat transfer performance of eight internally finned tubes was experimentally obtained under turbulent flow conditions. The effect of roughness was found to be insignificant for the internally finned tubes tested. These tubes showed promise for a heat transfer performance improvement of 25 to 170 percent for a given pumping power.

The twisted tapes were tested for augmentation in the laminar flow region (Hong and Bergles [64]) where a 1000 percent enhancement in Nusselt number was confirmed with water and ethylene glycol, covering Prandtl number ranges of 3-7 and 84-192, respectively, with the two fluids. The experiments were conducted for uniform-heat-flux boundary conditions in a 10.2 mm electrically heated stainless steel tube employing twisted tapes with twist ratios of 2.45 and 5.08. Hong and Bergles [64] developed a correlation scheme for heat transfer and pressure drop that was later extended to non-Newtonian fluids (Manglik et al. [222]). The work of Hong and Bergles [64] was extended to include static-mixer inserts and internally finned tubes (10 longitudinal fins, 1.57 mm height, in a 14.2 mm tube) for process-industry applications (Marner and Bergles [90]). These devices were found to provide a higher heat transfer enhancement ratio compared to the pressure drop penalty in the laminar region as compared to the turbulent region where increases in pressure drop were significant. The study was extended to laminar flow with Polybutene 20 (a liquid polymer manufactured by Chevron Chemical Co., Prandtl number range 1260-8130) by Marner and Bergles [147]. It was found that the internally finned tubes yielded a 400 percent increase in heat transfer coefficient for heating, while the twisted tape inserts were more effective for the cooling applications, yielding 150 to 225 percent improvements over plain tubes. The internally finned tubes yielded only marginal improvements during cooling.

The twisted tape insert results were analyzed (Manglik and Bergles [182]) in an effort to develop a correlation to predict their performance with laminar flow under uniform-wall-temperature conditions. The experimental data on heat transfer indicated a strong influence of five parameters: entrance effect, fluid viscosity ratio (bulk to wall conditions), Prandtl number, tape twist ratio, and swirl flow Reynolds number. The augmentation of highly viscous laminar flow under constant-wall-temperature conditions was investigated in subsequent papers (Marner and Bergles [231], and Manglik and

Bergles [261]), in which extensive experimental data on heat transfer and pressure drop was reported.

The available experimental data for water, ethylene glycol, and Polybutene 20 obtained in earlier studies were correlated within  $\pm 25$  percent (Manglik and Bergles [182]). However, this correlation covered a limited range of parameters. In subsequent papers, Manglik and Bergles [264, 265, 277] presented mechanistic parameters to identify the effect of swirl on the flow field. The balance of viscous, convective inertia and centrifugal forces is used to predict the onset and intensity of swirl, as determined by the swirl parameter. Based on this mechanistic description, four regions are identified - viscous flow, thermally developed swirl flow, swirl-turbulent transition, and fully developed turbulent swirl flow. A continuous correlation covering these regions for uniform-wall-temperature conditions was developed. The correlation accurately represents the parametric trends, as well as the asymptotic values for different variables.

**Spirally-Grooved (Rope) Tubes.** With the large amount of heat transferred in power plant surface condensers, a tubeside enhancement of the heat transfer coefficient could result in considerable savings in the overall plant operation. Spirally-grooved tubes hold the promise of enhancing the heat transfer coefficients on both sides; they are one of the most cost-effective enhancement devices. Professor Bergles saw the need to develop a good correlation scheme for these tubes for design purposes. Rabas et al. [212] compiled a data bank of 458 data points from five different sources. They proposed a new correlation scheme to predict the heat transfer coefficient and friction factor for the spirally-grooved tubes with an overall average error of less than 10 percent with the existing data. This represents one of the most comprehensive correlation schemes which accounts for the geometrical factors and fluid characteristics. One of the benefits of this correlation is that it is possible to clearly see the parametric influences of different geometrical parameters on the performance, providing a valuable tool to the designer who is faced with the selection of an optimum geometry based on not only the thermal, but economic and manufacturing constraints also.

**Turbulators for Fire-Tube Boilers** Fire-tube boilers employ high temperature gases flowing inside tubes. Since the heat transfer coefficient on the outside is very high with boiling water, it is desirable to increase the heat transfer coefficient on the gas side. The overall objective in this application is to improve the boiler efficiency. Other factors such as pressure drop, air-fuel ratio, changes in the water side heat transfer coefficient, fouling, and manufacturing cost are also important. In an experimental study program, Junkhan et al. [138] and Bergles et al. [145] investigated three commonly employed turbulators in fire-tube boilers (two bent-strips and one twisted tape). The heat transfer enhancements for these three inserts were measured to be 125 percent, 157 percent and 65 percent over a plain

empty tube, while the corresponding increases in pressure drop were 1100 percent, 1000 percent, and 160 percent at a Reynolds number of 10,700. The width of the twisted tape was less than the tube diameter, and this contributed to the lowering of its heat transfer enhancement to about 50 percent of the next best tube, but the corresponding pressure drop was reduced dramatically.

In order to identify the effect of the inserts on the flow characteristics in a fire-tube boiler application, Nirmalan et al. [161] conducted visual studies on seven different bent-strip types of inserts. The heat transfer enhancement was measured to be between 175 and 285 percent at a Reynolds number of 10,000, with corresponding pressure drop increases of 400 to 1800 percent. The visual observations indicate that the flow disturbance is most severe in the region where the bent strip comes in contact with the tube wall. The flow remains relatively intact in the region where the bent-strip does not touch the wall. Increasing the number of contacting points would appear to increase the heat transfer coefficient, however with a further penalty in pressure drop. The perforated-strip insert indicates that the core region also plays an important role in the heat transfer mechanism. The effect of radiation between the strip in the core region and the wall was also seen to play an important role, warranting further studies on this aspect. In a subsequent study, Nirmalan et al. [164] tested three additional inserts. They also addressed the issues raised in their earlier investigation, Nirmalan et al. [161], by constructing separate inserts representing the core region and the wall region of the bent-strip insert. The results indicate that the inserts with more rounded bends have a higher heat transfer coefficient as well as a higher pressure drop penalty. The pitch was seen to play an important role in the entrance region. The-core region insert was shown to enhance the heat transfer much more than the wall region insert, contrary to the earlier assumption that the core may not play as important a role. However, the combined effect of the two regions could be different from the individual influence of each region. Nirmalan et al. [180] presented a theoretical model using a surface renewal/penetration concept to develop a correlation scheme for the bent-strip inserts. In this model, they assumed that a packet of fluid is thrown toward the wall by the insert in the core region. This fluid is heated by the wall during a transient conduction process. The correlation scheme incorporates a constant that is characteristic of the individual insert.

Ravigururajan and Bergles [251] also visually investigated the flow phenomenon near the wall of ribbed tubes. Flow visualization was seen as a useful tool in optimizing the ribbed geometries.

**Twisted tape Inserts with Non-Newtonian Fluids.** Non-Newtonian fluids are often encountered in chemical, petroleum, food, biochemical, and pharmaceutical industries. Typical fluids in these applications are paints, inks, soap and detergent slurries, polymer solutions, greases, bitumen, paper pulp, corn syrup, mayonnaise, and starch suspensions, which are pseudoplastics. The three basic mechanisms of augmentation, (i) secondary flow effects, (ii) an increased flow path, and (iii) fin effects, are still responsible for



enhancement in non-Newtonian fluids. Manglik et al. [222] conducted an extensive study to investigate the heat transfer and pressure drop for laminar flow of non-Newtonian fluids in uniformly heated tubes with twisted tape inserts. The experiments were conducted with two concentrations, 1.0 and 1.3 percent, of HEMC solution in a 12.85-mm-diameter stainless steel tube. They attributed the increase in heat transfer coefficient with pseudoplastics in single-phase flow to (i) the non-Newtonian effects, and (ii) the variable consistency effects. Using the same correction factors, the Hong and Bergles [64] correlation for the uniform-heat-flux boundary condition was modified to predict the heat transfer results within  $\pm 30$  percent. This is quite remarkable, considering that the Hong and Bergles [64] could predict their own water and ethylene glycol data to only within  $\pm 25$  percent. Similar treatment resulted in a reasonable agreement with pressure drop data as well [ $+25$  percent to  $-30$  percent].

**Natural Convection.** Natural convection heat transfer is an important mode of heat transfer employed in many applications including cooling of microelectronic devices. It is desirable to extend its applicability to avoid the need for an active device such as a fan or a blower in the cooling system. Augmentation of natural convection heat transfer, therefore, has received renewed interest in last decade.

A systematic study was undertaken by Professor Bergles to investigate augmentation of natural convection heat transfer. Bhavnani and Bergles [157, 239] conducted an interferometric study of laminar convection heat transfer process from an isothermal vertical plate with two types of transverse elements - transverse ribs and transverse steps, placed horizontally across a 127-mm x 178-mm aluminum plate. A Mach-Zehnder interferometer was used for taking local measurements. The effect of pitch, height, and width (in case of ribs) was investigated. It was found that the transverse ribs, in fact, decrease the overall heat transfer rate by creating stagnation zones on both upstream and downstream sides of the ribs. The stepped surfaces helped to improve the performance. The effect of a sinusoidal wavy surface was studied by Bhavnani and Bergles [213, 252]. This geometry resulted in average heat transfer rates very close to plain-surface values. There was an effect of wave amplitude seen in the results. Smaller amplitudes caused the transition to turbulence at lower Grashof number values of around  $2 \times 10^7$  as compared to a plain vertical surface. It was found that if the lower edge of the plate was curved inside, it resulted in a better performance; however this effect was not significant when two or more cycles of the wavy surface were present along the plate length.

**Fouling In Enhanced Surfaces.** Fouling in heat exchanger tubes is a major issue that needs to be addressed before enhanced tubes can be employed, especially in critical applications such as utility condensers. With this objective, Somerscales et al. [250], and Bergles and Somerscales [290] carried out an extensive testing program on tubes employing four types of enhancement techniques, namely, the roped or corrugated, helical fins, axial fins, and helical rib

roughness. They conducted the tests with magnesium oxide (approximately 3  $\mu\text{m}$  diameter) as the foulant suspended in distilled water. The tests showed that the tubes with axial fins, helical fins, and rib roughness exhibited a higher fouling rate than a smooth tube under both high velocity and low velocity tests, whereas the roped or corrugated tube showed a remarkably lower fouling rate. However, Bergles [273, 278] reported a review of other works in which the field testing of roped or corrugated tubes showed considerably higher fouling rates with river and sea water. They attributed the main reasons for this discrepancy to the differences in the nature of the fouling elements present in the laboratory testing and the field testing. The water in the field tests contained dissolved salts, biological substances, finely divided sand or silt, and other products of chemical reactions, while the laboratory tests were conducted with a single foulant.

**Performance Evaluation Criteria for Single-phase Enhancement.** Thermal equipment designers are often faced with the task of selecting an appropriate enhancement device for a given application. Many researchers were working on developing guidelines to help in this selection process during 1960s and 70s. Bergles [19] presented a comprehensive survey of different augmentation techniques, and identified the need to establish generally applicable selection criteria for augmentative techniques. The factors such as development cost, initial cost, operating cost, maintenance cost, reliability, and safety are important in this selection process, but are too difficult to evaluate for general application. The enhancement ratio in heat transfer coefficient, at constant pumping power, length, and diameter, was used to compare different single-phase enhancement techniques. In a subsequent paper, Bergles et al. [45] proposed the eight performance evaluation criteria for augmentation devices. The parameters used in these criteria are - basic geometry, flow rate, pressure drop, pumping power, and heat duty, while the three possible objectives considered are - increase heat transfer, reduce pumping power, and reduce heat exchanger size. With these parameters, the following eight criteria were proposed - (i) for fixed geometry and flow rate, increase heat transfer, (ii) for fixed geometry and pressure drop, increase heat transfer, (iii) for fixed geometry and pumping power, increase heat transfer, (iv) for fixed geometry and heat duty, reduce pumping power, (v) for fixed heat duty and pumping power, reduce exchanger size, (vi) for fixed heat duty and pressure drop, reduce exchanger size, (vii) for fixed heat duty and flow rate, reduce exchanger size, and (viii) for fixed heat duty, flow rate, and pressure drop, reduce exchanger size. They derived specific ratios for each criterion. To include economics, a ninth criterion was introduced by comparing the total annual cost with, and without, augmentation. These criteria have been extremely helpful in convincing the heat exchanger industry of potential benefits of switching to enhanced geometries.

Bergles et al. [59] further modified the performance evaluation criteria to remove the assumption of constant temperature difference



between the hot and cold streams, and to include the effect of the thermal resistances external to the enhanced surfaces. Bergles et al. [62] applied these criteria in the selection of compact heat exchanger surfaces. Webb and Bergles [123] presented algebraic formulations of these criteria for low Reynolds number flows. These criteria are now widely used in the development and selection of compact heat exchanger surface geometries in automotive, air separation, and many other industrial applications. Applying these criteria to the bent-strip inserts in fire-tube boilers, Webb and Bergles showed that a favorable enhancement is achieved in the Reynolds number range of 5000 to 30,000 under a constant pumping power constraint, while the range drops to between 3000 to 5000 under the constant pressure drop constraint.

### **2.1.2 Enhancement In Pool Boiling.**

**Vibration and Ultrasonic Techniques.** The instantaneous reduction in pressure in the liquid adjacent to a heated surface leads to rapid growth and collapse of vapor bubbles resulting in enhancement in subcooled pool boiling. Such effects of vibration on the subcooled pool boiling heat transfer were studied by Bergles [17] with water as the working substance. An increase in vibrational energy markedly increases the pool boiling heat transfer rates. Also noted was the effect of vibration on the CHF.

Park and Bergles [199] studied the effects of ultrasonics on the heat transfer performance of a smooth pool boiling surface for possible microelectronic cooling applications. They used refrigerant R-113 as the test fluid. The results obtained were similar to those obtained by Bergles [17] in that little enhancement was observed for saturated conditions. Enhancement improved with the subcooling. Burnout heat fluxes were not significantly altered with the ultrasonics.

**Low-Finned and Modified Structured Surfaces.** The meticulous work by Professor Bergles in revealing the nature and mechanism of nucleate boiling in enhanced surfaces has been outstanding. He combined experimental measurements with visual techniques in revealing the flow of liquid in micropores and channels of enhanced boiling surfaces. His work provided a clear direction for industry in improving the performance of enhanced pool boiling surfaces.

Low-finned tubes were used in pool boiling applications since the 1940s. New surfaces with porous coatings and modified low-finned tubes were manufactured commercially under the names such as High Flux, ECR40, Thermoexcel-E, and GEWA-T. The standard GEWA-K profile is a low finned surface, while GEWA-T is a modified surface in which the GEWA-T fins are formed into a T-shape by indenting a notch in the tip of the fin and then press-rolling the tip. To understand the mechanisms responsible for the higher performance of the GEWA-T surfaces, Ayub and Bergles [156, 181] conducted an experimental study to compare the pool boiling heat

transfer rates for GEWA-T and GEWA-K surfaces. Both surfaces showed more enhancement with R-113 than with water, (maximum enhancement of 100 percent and 60 percent, respectively, with R-113 and water). One of the highlights of the performance of these tubes was the lack of a temperature overshoot at the onset of nucleate boiling. Comparing the performance of various geometries, Ayub and Bergles observed that the gap width between the fins was an important parameter in the thermal performance. The performance of a particular geometry was dependent on the fluid employed - so the idea that each geometry needs to be optimized for specific refrigerant was proposed. The study of the flow pattern near the boiling surface revealed that a predominant pattern of liquid inflow was present at different locations. Liquid entered the finned surfaces at specific locations while bubbles were generated at both sides of these locations. A continuous liquid-vapor exchange mechanism, different than the ones reported before for pool boiling, was observed for these surfaces. They proposed a heat transfer model which suggested that the heat transfer in this geometry is controlled by latent heat transport and agitated natural convection. Professor Bergles recommended that this study should be extended to CHF, and the performance of this geometry studied in tube bundles. This study represents a major step in the understanding and subsequent development of enhanced surfaces in pool boiling applications.

To enhance the performance of a GEWA-T surface further, Ayub and Bergles [196] proposed to fill the gap between the fins with a sponge material, polystyrene di-vinyl benzene polymer. The presence of the sponge was expected to increase the bubble activity in the gap. The pool boiling experiments were conducted on these filled surfaces with distilled water. Experimental results showed that the heat transfer rates increased by a factor of 1.5 to 2.3 relative to GEWA-T tubes with unfilled gaps.

Boiling hysteresis is caused by the fact that the superheat needed to activate a cavity is higher than that required to keep it active after it has been activated. Its effect is pronounced at the onset of nucleate boiling where the higher superheat requirement may cause the surface to overheat considerably before the pool boiling is established. Also, a vigorous explosion on the heating surface accompanies the onset of nucleate boiling in certain cases. The effects of hysteresis were seen to be a major problem in utilizing pool boiling in electronic cooling applications. Ayub and Bergles [214, 237] conducted an experimental study to characterize the hysteresis for GEWA-T surfaces. These surfaces exhibited a small but different kind of hysteresis in which multiple smaller excursions in wall temperature were observed during the transition from natural convection to nucleate boiling. They attributed this to improved natural convection in the low finned surfaces prior to nucleation. The multiple excursions were believed to be due to the isolation of nucleation sites from one another in the helical grooves.

Bergles and Chyu [104, 117, 127] present a study focusing on the hysteresis effect of structured surfaces in pool boiling. They showed that the tubes coated externally with porous metallic coatings showed considerable nucleate boiling enhancement once the nucleate

boiling was initiated. However, similar to smooth tubes, the enhanced tubes tested showed a hysteresis effect that was not reported in any earlier literature. The hysteresis was attributed to the wetting and flooding of the cavities by the liquid, particularly for refrigerants. Bergles and Chyu [127] discuss the problems encountered by temperature overshoot in different industrial applications. The effect of pore size and the heat transfer mechanism in tunnels formed by the microstructures are discussed by Bergles [215] in a comprehensive paper on this subject.

Professor Bergles extended the study of nucleate boiling with water on enhanced surfaces to pure refrigerants R-113 and R-11 and their binary mixtures as reported in Trewin et al. [282]. The tubes tested included smooth, knurled (Turbo-B), and sintered (High Flux) surfaces. Nucleation on these surfaces was initiated in some cases with a wall superheat of less than 0.1 °C. The hysteresis effect was most pronounced for small porosity High Flux surfaces, resulting in an overshoot of 10 °C. The porosity of the High Flux surface played a major role in the heat transfer process. Smaller porosity tubes performed the best (after the nucleate boiling was initiated following the hysteresis effect) among all the tubes tested. Another major conclusion of the study was that the sizes of the channel openings in Turbo-B tubes had very little influence on the heat transfer rate, indicating that the subsurface channel itself plays an important role. They identified thin film evaporation inside the channels as the main heat transfer mechanism in the Turbo-B tubes. The pool boiling heat transfer coefficients with mixtures showed a degradation for all three surfaces, although the enhanced surfaces consistently performed better than the smooth tube. A need for developing better correlating schemes for mixtures with enhanced surfaces was identified.

### **2.1.3 Enhancement in Two-Phase Flow, Boiling and Condensation.**

There is a need for improving the performance of heat transfer equipment incorporating boiling and condensation processes from an energy conservation viewpoint. The benefits to the refrigeration, power and process industry result directly in overall conservation of energy resources. With the rapid advancements in the enhancement techniques for single-phase heat transfer, it was only a matter of time before it was realized that further improvements in flow boiling and condensation heat transfer rates are warranted to improve the overall efficiency of the thermal systems. Professor Bergles addressed this need by conducting extensive research on enhancement in flow boiling and condensation.

#### **Doubly Rippled Surface for External Condensation.**

One of the most important factors in determining the external condensation heat transfer is the existing film thickness on the condensing surface. This layer presents a thermal barrier to heat transfer. In applying the pool boiling mode to electronic cooling, efficient condenser surfaces were needed to transfer the heat from the condensing refrigerant to the cooling water. In 1972, Markowitz et

al. [47] developed a doubly rippled surface; the main ripples help to drain the condensate film effectively from the downward facing condenser surface, while the secondary ripples reduce the film thickness on the condenser surface between the main ripples. An analytical formulation was presented to predict its thermal performance by extending the laminar film condensation theory. Although the experiments yielded a lower heat transfer rates than predicted by the theory, a number of practical problems arising in such research work were pointed out. These include the proper degassing procedure, the effect of non-condensables, and the assumption of non-uniform heat flux over the condensing surface.

#### **Twisted tapes, Internally Finned Tubes, Wall Roughness Elements and Microfins for In-Tube**

##### **Evaporation and Condensation.**

The work of Professor Bergles on twisted tapes in single-phase flow has provided an insight into the heat transfer mechanism, and a powerful correlation technique along with invaluable experimental data for this geometry. Professor Bergles saw the potential of twisted tapes in in-tube condensation application, and undertook a detailed study to explore this field. Although condensation enhancement was studied by many investigators, Professor Bergles pointed out that very few efforts were directed toward the in-tube enhancement.

Royal and Bergles [67, 85] conducted a detailed experimental study on the augmentation of in-tube condensation of low pressure steam in horizontal tubes by means of twisted tapes and internally finned tubes. Twisted tapes showed an improvement of 50 percent while the internally finned tubes showed an improvement of 300 percent in heat transfer rates over empty smooth tubes. To make the data useful to practitioners, Royal and Bergles presented correlations for both geometries, using their own data as well as other data available in literature.

The work on in-tube condensation with water was extended to refrigerants by Luu and Bergles [99] for application in refrigeration and air-conditioning. Twisted tape inserts and three different internally finned tubes were tested. Internally finned tubes performed better than twisted tapes. Using performance criteria with a constant pressure drop, internally finned tubes were by far superior, and held promise in commercial applications. Professor Bergles, however, pointed out that the fin geometries resulting in optimum performance for refrigerants are different than those for water. Luu and Bergles [103] presented qualitative reasons for the differences in condensation characteristics of water and R-113. The important parameter is the condensate film thickness, which depends on the surface tension, density ratio of the two phases and the wall shear stress. The twisted tapes were seen as possible retrofit devices in existing condensers.

The wall roughness elements, such as helical repeated rib and spirally fluted tubes, were found to be effective in enhancing the single-phase heat transfer. Professor Bergles investigated their performance for in-tube condensation. Luu and Bergles [114] and

Bergles [139] report that their experimental study on helical repeated ribs and the spirally fluted elements yielded 80 percent and 50 percent enhancement in the heat transfer coefficient over a smooth tube. Correlations for these geometries were proposed.

The use of microfin tubes for condensation application was extensively studied by Professor Bergles. Khanpara et al. [171] compared the performance of one plain and eight microfin tubes for in-tube condensation of R-113. The heat transfer coefficients improved considerably over smooth tube values. The main reasons for the enhancement during condensation were identified as the area increase due to fin effect, thinning of the condensate film, and the disturbances caused by the presence of fins. The effect of fin shapes, fin height, number of fins, and spiral angles were discussed. This information is useful to the manufactureres in the design of new and more efficient microfin geometries.

Microfin tubes were being introduced in refrigeration industry, and with the relatively little flow modification in the bulk flow, they offered a high heat transfer coefficient coupled with a low pressure drop penalty for evaporators as well. Khanpara et al. [165] conducted an extensive study on one plain and eight microfin tubes of different geometry to arrive at the optimum performing tube. They conducted experiments in electrically heated test sections over a range of quality, mass flux and heat flux. The result clearly identified the tube which performed best for refrigerant R-113 over the given range, and changes in the microfin geometry were proposed based on the observed trends.

Khanpara et al. [183] also conducted a study comparing the electrically heated and fluid heated test sections during evaporation of refrigerant R-113 in smooth and microfin tubes. The heat transfer coefficient was same for the two cases at low and medium mass flow rates; however for high mass flux rates, the electrically heated long test section gave 20 to 40 percent higher heat transfer coefficients. Further investigation is needed in this area.

Comparing various enhancement techniques proposed in the literature, Professor Bergles conducted a systematic study to evaluate their performance with refrigerants. Reid et al. [191, 249] compared the performance of five microfin tubes, and a smooth tube with a twisted tape insert, with the performance of two different diameter smooth tubes. The heat transfer coefficients and pressure drops were obtained for these geometries over a wide range of quality, mass flux, and heat flux. This work showed that the microfin tubes with helix angle around 16 to 18 degrees performed well, with a low increase in pressure drop.

The effect of fluid properties on the performance of microfin tubes of different geometries is an important area in refrigeration application. Khanpara et al. [192] compared the performance of different microfin tubes with R-113 and R-22 refrigerants over the range of operating conditions commonly encountered in refrigeration practice. The enhancement in heat transfer was similar with the two refrigerants in the high mass flow region. In the low mass flow region, enhancement was higher with R-113. They emphasized the need to develop a correlation scheme for microfin tubes. Schlager et

al. [230] present a detailed study on evaporation and condensation heat transfer in microfin tubes with R-22. The microfins showed considerable enhancements (factors of 2.3 to 1.6 for evaporation, and 2.0 to 1.5 for condensation). Corresponding pressure drop increases were only 20 to 40 percent. The effect of tube diameter on the performance was insignificant. This shows that a microfin geometry could be applied to different diameter tubes without any modifications. These studies clearly indicate the superior performance of microfin tubes in boiling and condensation. It is therefore no surprise to see their widespread use in refrigeration and air-conditioning industry.

The performance of several microfin tubes in a fluid heated test set-up was tested with Refrigerant R-22 by Schlager et al. [225]. The tests indicated that the performance of all microfin tubes appeared to be closer together. An increase in mass flow rate decreased the evaporative performance. The pressure drop penalty was less than the heat transfer increase, but it increased with increasing mass flow rate.

In practical applications, small amount of oil is generally present in evaporators and condensers of a refrigeration system. Schlager et al. [204] present a detailed study on the effect of oil on the evaporation and condensation heat transfer in a low-fin tube. Refrigerant R-22 was used with a 150-SUS naphthenic mineral oil. Small amounts of oil, below 1.5 percent, led to an improvement in the evaporative heat transfer coefficient for smooth tubes, but the low-fin tube showed very little enhancement. Higher quantities of oil degraded the evaporator performance for the low-fin tube below the smooth tube level. The condensation performance degraded with the presence of oil, but it was less adversely affected compared to smooth tubes. The work clearly showed that the presence of oil in refrigeration systems affects the thermal performance of augmented tube evaporators and condensers.

A similar study was conducted by Schlager et al. [209] to investigate the effect of oil on the evaporation and condensation heat transfer for smooth and microfin tubes. As found in earlier studies, the presence of oil improved the evaporation heat transfer coefficient of smooth tubes. Microfin tubes also exhibited similar trends, although the enhancement was less. The condensation heat transfer coefficient decreased with an increase in oil concentration for both tubes. They also discussed specific effects of oil concentration and mass flux. Subsequently, Schlager et al. [224, 233] found that the effects of 300-SUS oil were similar to those with 150-SUS oil.

Schlager et al. [228, 238] presented the results showing the effect of oil on the heat transfer and pressure drop performance of smooth and internally finned tubes with R-22. The performance trends of the finned tubes were similar to those for the microfin tubes, but were consistently below the microfin tubes. During condensation, both enhancement techniques resulted in lower heat transfer rates, as compared with the smooth tubes with the addition of oil.

Schlager et al. [235, 236] conducted a detailed literature survey and presented design-correlations for predicting the heat transfer coefficients with refrigerant-oil mixtures during evaporation and

condensation inside smooth and microfin tubes. These correlations are extremely useful to the designers of the heat transfer equipment.

The mechanisms responsible for degradation of heat transfer performance in microfin tubes with oil were not clearly understood. Ha and Bergles [270] conducted a careful study to investigate the effect of oil using visual observations and careful mass fraction measurements in the liquid film near the wall. They found that an oil rich layer adhered to the wall, and its thickness increased with oil concentration and mass flow rate. They identified the thermal resistance of this layer as the primary reason for the performance degradation.

**Twisted tapes in Dispersed-Flow Film Boiling** The swirl flow generated by twisted tapes could be effective in modifying the film-flow and heat transfer behavior in the dispersed-flow film boiling region. Bergles et al. [30, 40] conducted an experimental study to validate these findings experimentally. Their results show that up to 200 percent enhancement is possible with the introduction of a swirl generator in the flow. In this work as well, Professor Bergles considered the practicality of the enhancement device by comparing its performance under a given pressure drop or pumping power condition. Assuming that the swirl flow promotes thermal equilibrium in the two-phase flow, a model was proposed that requires only one “adjustable constant,” the fraction of the tube wall covered by the centrifugal droplets. With an optimized constant, the correlation described the data well.

#### **Enhancement in Film Evaporation**

Horizontal spray-film evaporators are employed in desalination, refrigeration, and chemical process operations. Their applicability to ocean thermal energy conversion systems was evaluated by Chyu et al. [130]. Since the ocean thermal energy systems work between small temperature differences, improving the performance of the evaporation and condensation processes in the power cycle is critical. In the evaporator, the nucleate boiling in the film would be important, and porous and microstructures, employed in pool boiling enhancement, are strong candidates. Chyu et al. tested five surfaces and found a considerable improvement over smooth surface performance. However, the performance with spray was below the corresponding pool boiling performance for these surfaces. They attributed the main reason for the poor performance to the unfavorable temperature profiles in the film.

The enhancement with the structured surfaces in falling-film evaporators was investigated by Chyu and Bergles [148, 232]. The surfaces tested include smooth, Wieland-Werke Gewa-T deformed low fin surface, Hitachi Thermoexcel-E tunnel-pore surface, and Union Carbide Linde High Flux porous metallic matrix surface. Falling-film evaporation over smooth surfaces yields higher heat transfer coefficients than the corresponding pool boiling values. The falling-film results for structured surfaces approach the pool boiling results over structured surfaces at high heat fluxes. Distinct effects

were seen in the convective and nucleate boiling mechanisms depending on the surface tested. Effects of film flow-rate and liquid feed-height were of secondary importance. The need was emphasized for investigating the structured surfaces with different fluids for specific applications.

## **2.2 Review Papers on Enhanced Heat Transfer**

One of the most significant contributions made to the technical community by Professor Bergles is in providing with state-of-art reports in many areas, including enhanced heat transfer. He started his work in this area in early 60s, and is still in the midst of publishing various review papers.

His first elaborate review paper on augmentation techniques appeared in 1969, Bergles [19]. He referenced 371 papers in this work, and classified them into following categories: vortex flows, including twisted tape swirl generators; vibration of the heater surface; electrostatic fields; and various types of additives. The non-boiling, boiling, and condensation in free and forced convection, and mass transfer in forced convection were covered. The review included key information from different papers, and offered guidance for practical applications by presenting turbulence promoter data in terms of a pumping power performance criterion. He reported important experimental data in figures, which were carefully drawn to include detailed information on the experimental conditions for which the results are presented. He compiled and presented the experimental investigations in a tabular form to bring out clearly their key features. Through this paper, Professor Bergles raised the standard for presenting the state-of-art review papers, and he himself wrote more than fifty such in-depth review papers on different aspects of heat transfer.

To aid the researchers in narrowing down their search to specific papers, and to help designers find specific references in their field of interest, Professor Bergles started preparing a bibliography of available literature on different topics. Bergles and Webb [35] presented the first such bibliography on augmentation of convective heat transfer. It included references to 472 papers. Professor Bergles then developed an extensive bibliographic collection, resulting in a six-part paper series coauthored with Professor Ralph Webb - [86] and [92] in 1978, [94] and [95] in 1979, and [102] and [105] in 1980. Even with the availability of the computerized on-line services, the exhaustive bibliographic collections, presented under specific categories, are valuable resource for researchers and designers since a computerized search is able to catch only a fraction of the available literature.

Professor Bergles kept pace with the developments in the enhanced heat transfer, and provided critical surveys, which were valuable in determining the potential of a given augmentation technique for a specific application. He constantly updated his reviews on augmentation, and published them periodically since 1969. Reviewing the augmentation of convective heat transfer, he has authored or coauthored the following papers - Bergles et al. [49],

[52], [66], [84], [88], [89], [109], [110], [111], [132], Bergles et al. [149], [151], [173], and [189]. References [153] and [154], published in 1986, deal with enhancement in high temperature applications. A major part of Professor Bergles' research activity was directed toward the enhancement in boiling and condensation applications. He presented his first paper in this area, Bergles [74] in 1976, and has steadily reported latest compilation of research work - [78], [134], [142], and [229].

Professor Bergles presented extensive review papers on the effects of temperature-dependent fluid properties on laminar flow heat transfer [119, 120] and enhancement techniques in the laminar flow region (Joshi and Bergles [129]). In laminar flow enhancement, his review papers, Joshi and Bergles [113] and Bergles and Joshi [122], provide an extremely valuable resource for selecting a specific type of enhancement device, and understanding the underlying enhancement mechanism occurring in it.

Professor Bergles classifies the enhancement techniques, implemented in last twenty years or so, as second generation heat transfer technology. Starting with the smooth tube as the first generation, the finned surfaces and the 2-D structured surfaces are classified under second generation enhancement technology. Starting in 1983, Professor Bergles has extensively reviewed the second generation enhancement devices in the following papers - Webb and Bergles [137], Bergles and Webb [141], [223], [255], [276], [291], and [296]. The current thrust of Professor Bergles' work, as described in his recent paper, Bergles [300], is toward the third generation enhancement technology that includes 3-D roughness elements, 3-D fins, microfins, and metallic matrices. Although some of these techniques have been invented many years ago, their widespread acceptance in industrial application really determines their "age."

### **2.3 Laminar Internal Flow**

Professor Bergles started his work on laminar internal flow with an extensive study of the effect of natural convection on heat transfer, in fully developed laminar flow of water inside a tube, with uniform heat flux at the wall (Newell and Bergles [23]). This study included the effects of the circumferential variation in the wall temperature by considering two limiting tube-wall conditions - infinite-conductivity tube, and glass-tube (having the same thermal conductivity of the wall material as the test fluid, water). At low Reynolds numbers, a secondary flow due to natural convection is established, which is symmetrical about the vertical plane passing through the axis of the tube. The flow field is three-dimensional, spiraling, in character. The governing differential equations employed stream functions, and were solved using a finite difference formulation. Results were presented in terms of detailed parametric relationships. To make the results useful to designers, correlations for Nusselt number, and a pressure drop parameter, (friction factor  $\times$  Reynolds number) were presented as functions of bulk temperature, heat flux, and tube radius. Computer limitations did not permit extensive solutions with

secondary flows in the entrance region. Bergles [34], in a later technical note, discussed the applicability of different assumptions, such as constant wall temperature, Prandtl and Reynolds number effects, and the entrance region effect.

After analyzing the combined convection problem analytically, Professor Bergles undertook the experimental work to verify the numerical results. Bergles and Simonds [41] conducted experiments with electrically heated, coated glass tubes, using water as the test fluid. The final correlation, presented in a graphical form, covered both, the developing and the fully developed flow regions. The heat transfer results were much higher (about 3 times higher for a Rayleigh number of  $10^6$  in the fully developed region) than the corresponding constant property solution. In this work, Professor Bergles has shown a mastery in designing experiments to obtain meaningful information regarding a phenomenon, while providing useful design correlations to engineering practitioners. We see this throughout his experimental work in many different areas.

Hong et al. [57] extended the numerical and experimental work to combined convection in electrically heated metal tubes. Their results agree with theoretical analysis; the results for the metal tube lie between the constant heat flux and the constant wall temperature cases. A correlation was presented for Nusselt number by including a parameter representing the ratio of the fluid to wall thermal conductivities. Morcos and Bergles [61] included the effect of variable properties in the laminar fully developed region. The mean film temperature was employed to account for the property variations rather than a viscosity correction factor. Hong and Bergles [69] presented analytical solutions for the combined convection with fully developed laminar flow in a circular tube by considering the temperature-dependent viscosity. The results were then correlated in simple forms to cover a wide range of parameters. The results with variable properties lie 50 percent above the results for the constant property solution.

To gain a further insight into the heat transfer mechanism with twisted tape inserts, Hong and Bergles [65] studied the laminar heat transfer in the entrance region of a semicircular tube with uniform heat flux. They later employed the results of this work in the models developed for twisted tape inserts. Hong and Bergles [83] present the analytical solutions for developing and developed flows, and show that the heat transfer rate is increased by 200 percent, and the entrance region is reduced to one-tenth, by including the variable property effects.

Joshi and Bergles [106, 108, 125] analyzed laminar flow heat transfer in circular tubes, with uniform wall heat flux, for non-Newtonian fluids. They compared the results of the analytical study with available correlations. Using their own experimental data covering a broad range of parameters, they presented two correlations based on the temperature dependence of the rheological characteristics of the fluid. Joshi and Bergles [118, 129] extended the study to the uniform wall temperature case.

The papers by Professor Bergles on enhancement in laminar region are summarized in Section 2.5 under review papers.



## **2.4 Heat Transfer to Refrigerants (Boiling and Condensation Heat Transfer)**

A major part of Professor Bergles' research work has been directed toward the refrigeration industry. His work on the enhanced tubes (especially microfin tubes) for boiling and condensation is noteworthy, and is covered under section 2.1.3. In this section, his work on other aspects of heat transfer to refrigerants is covered.

Although much of the research in academia is directed toward pure refrigerants, most refrigeration systems employ oil refrigerant mixtures to provide lubrication to the compressor in the system. With fluorinated hydrocarbon refrigerants, oil is soluble in refrigerant, and is carried over from compressor to condenser and evaporator. Baustian et al. [158] report a study summarizing predictive methods for thermophysical and transport properties of oil-refrigerant mixtures. To determine the oil concentration in the mixture, Baustian et al. [159, 170] reviewed different electrical and optical properties as possible bases for real-time measurements. They recommended two types of measurements - capacitance measurement and refractive index measurement. Continuing this study into the experimental phase, Baustian et al. [206, 207, 208] built and tested three concentration measuring devices based on the density, viscosity, and acoustic velocity respectively. These devices provide practical solutions in the refrigeration industry for on-line measurement of oil concentrations.

Continuing with the practical problem of oil-refrigerant mixtures, Manwell and Bergles [242] presented an experimental study of gas-liquid flow patterns with Refrigerant R-12. They conducted the study with smooth and micro fin tubes. The presence of oil caused foaming, which wetted the walls, and formed foamy slugs in the evaporator. This explains the improvement in the heat transfer coefficient with addition of oil to pure refrigerants in smooth tubes. Since the wetting phenomenon is already present in micro fin tubes, the presence of oil does not necessarily improve the heat transfer. Further, they did not observe the foaming behavior in microfin tubes. This study seems to be the first one to address the mechanism of enhancement with oil-refrigerant mixtures in smooth and microfin tubes.

The oil concentration in evaporator and condenser plays an important role in the heat transfer mechanism. Schlager et al. [243] measured these oil concentrations as functions of heat and mass fluxes, and exit superheat. As expected, with the exiting refrigerant closer to saturation, the oil concentration in the evaporator increased. The experiments showed that the concentrations in the evaporator were as much as three times, and those in the condenser were about twice the average concentration in the system.

Professor Bergles conducted extensive heat transfer measurements in evaporators and condensers with oil in smooth and microfin tubes. This work is reviewed under section 2.1.3 under enhancement in two-phase flow.

Stratification effects in horizontal evaporators cause circumferential variation in heat transfer coefficient. Ha and Bergles

[271] conducted a detailed experimental study to measure this variation as a function of other system parameters. The effect of axial wall conduction influenced the heat transfer coefficient by only 10 percent. In runs with clearly separated flow, the heat transfer coefficient at the base was 3-5 times higher than the average value. The importance of liquid film for evaporation is confirmed, indicating severe deterioration in heat transfer in the upper part of the tube exposed to vapor in the stratified flow.

Ha and Bergles [284] present a valuable discussion on the effect of the type of heating on the heat transfer mechanism in boiling systems. They compared electric resistance wire heating, direct electric heating, and liquid heating, and listed advantages and disadvantages of each method. The paper provides valuable insight on the heat transfer mechanism in smooth and microfin evaporator tubes, with pure refrigerant and oil-refrigerant mixtures. The dryout toward the exit of the evaporator is delayed with microfin tubes, resulting in a significant increase in the heat transfer performance of these tubes.

## **2.5 Fundamental Studies and Reviews of Two-phase Flow and Boiling Heat Transfer (Including Boiling, and Two-phase flow Instabilities)**

Professor Bergles addressed many current issues in two-phase flow, boiling heat transfer, and CHF under different configurations - pool boiling, subcooled flow boiling, and saturated flow boiling. To cover his contributions, his publications in these two broad areas are presented under the following specific subsections.

### **2.5.1 Two-phase Flow Regimes and Flow Structure.**

Flow patterns in two-phase flow were studied by early investigators with air-water, and oil-gas systems under adiabatic conditions. To understand the heat transfer in high pressure boilers applied to the nuclear industry, Bergles and Suo (9) undertook an experimental study to identify the flow patterns under diabatic conditions. They investigated the effect of tube length, system pressure, mass flux, and inlet subcooling in vertical upflow. They identified the flow regimes primarily with an electrical resistance probe. They also took high-speed still pictures, but the resistance probe was found to be more useful in establishing different flow patterns. Changes in pressure, tube length, and inlet temperature significantly affected the flow regime boundaries. Bergles et al. [11] conducted a similar study with low pressure water, and developed composite flow pattern maps to illustrate the effects of pressure, length, and inlet temperature on the flow regime boundaries. Focusing on the spray annular regime, Bergles and Roos [15] measured the film thickness, and obtained the first evidence of smooth dryout at low velocities. The film produced a fluctuating signal in the electrical probe, pointing to a possibility of nucleation, or entrained vapor, in the film close to the dryout conditions.

Professor Bergles realized the importance of two-phase flow in rod bundles as applied in nuclear steam generator application. Bergles [26] investigated the two-phase flow structure visualization with high pressure water in a rod bundle, and found significant differences in flow patterns in different subchannels. Using the electrical resistance probe, he measured the film thickness in the subchannels, and reported extensive data on flow regimes as a function of quality and mass velocity. Significant differences were also reported between the diabatic and adiabatic conditions. The flow regime boundaries were shifted to lower quality with heat addition. The electrical probe was thus seen as a useful tool in sensing an imminent CHF condition.

Another aspect investigated by Professor Bergles was the two-phase critical flow under diabatic conditions, which is relevant in studying the accident conditions in nuclear reactor safety analysis. Bergles and Kelly [27] conducted experiments with water, and found that for qualities below 0.04, the earlier models developed for diabatic flow underpredicted the flow rate.

### **2.5.2 Two-Phase Flow Mechanism, and Instabilities.**

Evans et al. [20, 32] studied the propagation of shock waves in different two-phase flow regimes with air-water flows. The presence of entrained liquid mist was confirmed to have an enormous effect on the pressure wave propagation, and little or no acoustic energy was transmitted through the liquid film. The flow regimes, such as slug flow and annular flow, influenced the pressure wave propagation considerably. This fact explained some of the discrepancies in the data reported earlier in literature. Yadigaroglu and Bergles [31] conducted experiments with Freon-113 to study the density wave oscillations, and observed higher mode oscillations, transmitting at a fraction of the transit time through the channel. They also presented a stability map to explain the phenomenon.

**2.5.3 Instrumentation In Two-phase Flow** Professor Bergles refined the art of experimentation by using many new instrumentation techniques. In one of his papers, Bergles [21] presented an excellent survey of electrical probes in the study of two-phase flows. He described the core-wall conductivity probe used in determining the flow pattern, void fraction, and liquid film thickness. This study provides a very useful source to anyone who wants to develop these probes. Also, he compared the accuracy of measurements of the electrical probes with other techniques.

More recently, Bonetto et al. [253] used a hot wire anemometer, and developed a probability density function to obtain the information regarding void fraction, bubble size, and vapor velocity from flow boiling experiments. Carvalho and Bergles [254] further applied the hot wire anemometer to measure the local void fractions in pool boiling of FC-77 over small vertical heaters, simulating immersion cooling of electronic chips. The low contact angle of FC-77 yields in

a more satisfactory discrimination between the two phases. They also found the optimal sensor temperature corresponding to 60°C, which was much higher than those reported in earlier studies.

**2.5.4 Pool Boiling Heat Transfer.** Pool boiling heat transfer data is generally obtained under steady-state conditions. Thompson and Bergles [28] investigated the applicability of the pool boiling curve to quenching problems. They found large differences between the quenching data and the predictions from pool boiling correlations. The presence of surface deposits on the material being cooled disturbed the vapor film and caused early transition to nucleate boiling, thereby reducing quench times below the conventional boiling predictions. Further, it also implied that the transient techniques are not suitable for obtaining the steady-state pool boiling curve.

Another major factor affecting pool boiling data in industrial applications is the presence of contaminants. Jensen et al. [97] experimentally studied the effect of Cosmoline, JP-4, turbine oil, and phosphate on the pool boiling curve. The presence of Cosmoline improved heat transfer rates, the highest coefficient being obtained at the highest concentration tested (1000 ppm). However, DNB occurred at lower heat fluxes compared with distilled water. JP-4, on the other hand, had no influence on heat transfer or DNB. Turbine oil produced erratic results, sometimes causing explosive bubble formation on the heater surface. At high concentrations, the heat transfer results were dramatically below the distilled water curve. DNB was also decreased with the addition of turbine oil. Addition of phosphates generally shifted the contaminant pool boiling curve back to normal, though the DNB occurred at the same level as with the contaminants. The orientation, vertical or horizontal, did not affect the boiling characteristics with or without contaminants.

Carvalho and Bergles [283] studied pool boiling over small vertical heaters, similar to electronic chips, and identified different regimes, rogue sites, incipient boiling, patchy nucleate boiling, fully developed nucleate boiling, and vapor coalescence (leading to dry patches). Using a hot wire anemometer, they obtained void fraction profiles near the heater surface as a function of heat flux. They established the formation, and subsequent propagation of dry patches as the mechanism leading to CHF in pool boiling.

**2.5.5 Subcooled Flow Boiling Heat Transfer.** In one of his first papers, Professor Bergles presented an often referenced paper on the forced convection boiling heat transfer with Professor Rohsenow, Bergles and Rohsenow [4]. They analyzed flow boiling heat transfer with subcooled and saturated liquids, and presented a criterion to determine the size ranges of nucleating cavities for a given superheat and flow conditions. Also, the heat transfer rates in the region between the forced convection and the fully developed boiling is interpolated using the inception point as the starting point

on the line representing forced convection heat transfer, and merging with the fully developed boiling curve. This inception condition is still widely used in the current literature in many different geometries, from smooth tubes to complex ink jet printer heaters.

Bergles and Dorrer [18] conducted extensive experiments to study the pressure drop in subcooled boiling of low pressure water in 2.5-4.0 mm diameter tubes. The pressure drop data was then correlated in a chart form, and curves were presented to cover the entire data. This was one of the first studies in this area. The information is useful in studying stability of multichannel systems as well.

Professor Bergles studied the nucleation phenomena in subcooled boiling systems, and noted that a larger amount of superheat is needed for a given cavity than predicted from theoretical considerations. Murphy and Bergles [43] attributed this effect to the dissolved gases that increased the total pressure in a cavity. However, it was found that with fluorocarbon systems, large superheats were required to initiate nucleation. This caused the "hysteresis" effect, which they attributed to the total flooding of the cavities with low contact angle fluids, such as fluorinated refrigerants. The commercially available porous surfaces tend to prevent the deactivation of the cavities.

Vandervort et al. [266] studied the subcooled flow boiling of water in a 2 mm diameter tube under high heat flux boiling. They observed streams of small diameter bubbles (estimated to be 3  $\mu\text{m}$ ) at the exit section of the tube. They presented a detailed description of the forces acting on the bubble and the associated heat transfer mechanism. They believed that Marangoni force was the dominant force, followed by surface tension and drag. The discussion presented in the paper provides a good basis for developing a mathematical model describing subcooled boiling heat transfer near CHF.

Tong et al. [294] investigated pressure drops in small diameter tubes with subcooled flow boiling of water. The earlier work by Bergles and Dorrer [18] was extended with 1.05-2.44 mm diameter stainless steel tubes. The subcooled boiling pressure drop was found to be directly proportional to mass flux and length to tube diameter ratio, but inversely proportional to the tube diameter. They developed a pressure drop correlation which is particularly useful in designing cooling systems to accommodate high heat fluxes.

#### **2.5.6 Flow Boiling Heat Transfer In Enhanced Tubes.**

This is covered earlier in the section on enhanced heat transfer, Section 2.1.3.

**2.5.7 CHF In Pool and Flow Boiling.** CHF studies are important in designing flow boiling systems for cooling high flux systems, such as electromagnets. These devices use narrow diameter passages due to space restrictions. Much of the CHF data in

literature pertained to large diameter tubes. To close this gap, Bergles [5] undertook a detailed experimental plan to generate data on CHF for flow of water in 1.5 to 4 mm diameter, electrically heated, stainless steel tubes. Small diameter tubes were found to give a higher CHF than large diameter tubes, making them especially suitable for high-flux cooling systems. Flow oscillations due to an upstream compressible volume was found to reduce the burnout heat flux considerably. Earlier studies which recorded a lower CHF were believed to be affected by this problem. Bergles et al. [11] and Bergles and Kelly [27] conducted additional experiments with subcooled water at low pressure. Choked flow was found to be prevalent under these conditions. CHF was found to be a complex function of both local and inlet conditions.

High pressure water is used in power generation systems, and CHF data is needed in designing these systems. Spray-annular flow pattern occurs at higher qualities, and is of interest in most two-phase systems. Bergles and Roos [15] conducted experiments in recirculating high-pressure steam loop, which reduced the expenditure considerably. Film thickness was measured with an electrical probe, and was found to gradually decrease to zero as the CHF was approached. Measurements in rod-bundles indicated wide variations in film thickness over tubes.

Professor Bergles extensively used many visualization techniques to obtain a good physical picture of complex phenomena. Fiori and Bergles [25] developed a series of films to study burnout in subcooled flow boiling.

Utilizing the experimental data and the photographic information of the CHF phenomenon, Fiori and Bergles [33] proposed a model in which stable dry spots are formed underneath bubbles, and these spots can no longer be quenched at higher heat fluxes, leading to vapor patches covering the heater surface. They presented a comprehensive discussion on possible mechanisms leading to CHF based on the information from Fastax (1200 frames per second) camera and microflash photos.

Bergles [60, 72] surveyed the available literature and provided a comprehensive coverage on the description of the burnout phenomenon in pool boiling with different heater configurations, and different CHF augmentation techniques. This paper presents useful summary, and more importantly, future directions for researchers. Similar reports were presented by Bergles [73] for the low quality forced convection systems, and by Bergles [100] for the high quality forced convection systems. These comprehensive surveys provide a clear picture of the parametric trends and effects of important system variables on CHF. For the pool boiling systems, Park and Bergles [195] collected 2237 data points for CHF and fitted polynomial curve fits to provide engineering equations for system designers.

In a shell and tube evaporator, the tube length covered by baffles may be considered to be under pool boiling conditions. Since the liquid supply is restricted, the burnout condition could be initiated at this location. Jensen et al. [70] studied the dryout in pool boiling under restricted annular geometries and found that the dryout condition occurred at lower clearances and larger widths of baffle



coverage. However, the pool boiling curve shifted to the left, indicating a more efficient heat transfer under the restriction. Jensen et al. [70] attributed this increase to the thin film evaporation in the clearance space.

CHF remains a major concern in high heat flux systems. Vandervort et al. [241] conducted an experimental study in forced convection systems with water in stainless steel tubes having diameters ranging from 0.3 to 2.7 mm. Mass fluxes ranged from 5,000 to 40,000 kg/m<sup>2</sup>-s, and subcoolings ranged from 40 to 135 °C. In some preliminary tests, a maximum heat flux of around 10<sup>8</sup> W/m<sup>2</sup> was achieved. The CHF was shown to increase with both velocity and subcooling. Small diameter tubes provided a higher CHF. More detailed data are presented by Vandervort et al. [280].

In cooling of electronic chips with pool boiling liquid, the heater thickness affects the CHF. Carvalho and Bergles [259] studied this effect, and found that none of the conventional parameters such as wall capacitance, thermal conductivity, or thermal diffusivity were able to correlate the CHF data well. Carvalho and Bergles [259] verified the new parameter "compacitance", which consists of the heater thickness, and heater material thermal properties. Although a considerable data spread is still observed, this work represents a major step in formulating CHF for thin heater geometries. Using the same parameters, Golobic and Bergles [260] proposed a new correlation which correlated their own experimental data for strips cooled on both sides with an average absolute deviation of less than 10 percent.

The mechanism of saturated pool boiling CHF was discussed by Bergles [257]. The two competing theories, hydrodynamic stability theory and microlayer dryout interpretation were discussed. Knowledge of the flow pattern near CHF was deemed necessary to clarify the situation for flat heaters, which forms the basis for other geometries as well.

**2.5.8 CHF in Helically Coiled Tubes.** Helically coiled tubes are used in industries for single-phase, evaporating and condensing flows, and many other applications. At the system start up, the subcooled boiling conditions sometime lead to the CHF condition, which is not well studied in the literature. Jensen and Bergles [107, 126] conducted experiments to obtain CHF data with R-113 in 0.762 mm diameter tubes. The data was correlated and it was found that an additional parameter consisting of non-dimensionalized radial acceleration was able to account for CHF in helically coiled tubes. The CHF in these tubes was lower than the straight tubes. Undesirable upstream dryout was found to occur if the coil was operated under low subcooling or low quality near the inlet, and in the high quality region near the exit.

Jensen and Bergles [131] studied an interesting problem of practical importance in solar energy applications. A helically coiled tube in this application experiences a higher heat flux on the outside surface receiving the solar energy directly. Such a heat flux tilt was found to reduce the CHF. Jensen and Bergles predicted that the liquid film was disrupted with the heat flux tilt. They correlated the

data in terms of an additional parameter representing the maximum to average heat flux ratio. The problem of non-uniform circumferential heating is of interest in nuclear applications as well.

### **2.5.9 Reviews and Summary of Two-phase Flow and Boiling Heat Transfer.**

Professor Bergles directed his efforts to promoting a clear understanding of many heat transfer phenomena through critical literature reviews. He also placed a major emphasis on the undergraduate education, as is clearly seen in his publication dealing with laboratory experiments demonstrating the bubble behavior in pool and flow boiling, Bergles and Griffith [12]. The experiments were designed to visualize the bubble behavior with varying subcooling, and varying velocity as well in forced flow boiling.

An overview of current information and its relevance to specific applications is essential to keep the researchers in tune with the needs of the industrial community. In one of his early papers, Bergles [96] provided such a link by indicating future needs in two-phase flow research. Multi-beam x-rays, rotating heat pipes, OTEC power plants, and PWR reactors were the examples he used in identifying the research topics requiring further attention.

Bergles [112] presents a good description of heat transfer mechanisms associated with reactor thermal-hydraulics. He discussed incipient boiling, nucleate boiling, burnout, post-dryout, and quenching. The quenching phenomenon is of interest in reactor cooling under accident conditions. Additional effects due to the transient nature of the process makes it different than that described by the steady-state pool boiling curve.

Continuing in the area of nuclear thermal-hydraulics, Bergles [135] presented a comprehensive picture of the heat transfer related issues related to PWR and BWR reactor systems. The specific issues related to boiling heat transfer are then discussed in further detail. Bergles [144] provides some of the empirical correlations used in the steady-state and transient analysis of nuclear reactors.

Boiling heat transfer is a complex phenomenon, and many research papers are published every year. It is therefore very difficult for design engineers of two-phase heat exchangers to keep track of latest developments. Bergles [188] presented clear information on various heat transfer mechanisms in two-phase heat exchangers. He also compared various design correlations, and made specific recommendations. It should be a useful reference for anyone planning to work in this area, and also for those who want to clarify some of the difficult concepts underlying theoretical models available in the literature. Bergles [269] provides similar information on boiling heat transfer pertaining to a single tube in a large pool, and a single vertical tube. This work provides a basis for studying boiling in other more complex geometries such as rod bundles, and multiple vertical channels.

## 2.6 STUDIES AND REVIEWS OF COOLING OF ELECTRONIC COMPONENTS

Bravo and Bergles [68] reported the performance of a small enclosure with one wall heated and the other wall cooled, and evaporating-condensing liquid/vapor in the enclosed space. They studied the effect of power level, heater geometry, and dissolved gases on the heat transfer rates. This geometry is of practical interest in electronic cooling applications.

Bergles et al. [81] present a “representative” survey of the state-of-the-art, (1977), of heat transfer technology in electronic packaging. They identified that the air cooling would continue in a wide spectrum of cooling applications, including portable devices and medium to large systems. Direct liquid cooling then appeared to be reaching “maturity,” but was not quite ready for industrial applications. Liquid rejection systems, such as heat pipes, and sophisticated technologies were expected to migrate from laboratory to industrial products. They predicted that computer analysis tools would become standard in the thermal design of electronic packages. Looking back, their conclusions drawn in 1977 seem to be right on target.

Bergles [82] presented a paper on the evolution of cooling technology for electrical equipment and electronic devices. He quoted Mouromtseff from his 1942 paper as writing “Without exaggeration one may state that in designing electronic tubes there are more mechanical, metallurgical, and heat engineering problems than those of pure electronic in character.” This statement was true when Mouromtseff wrote it in 1942, was valid when Professor Bergles quoted it in 1977, and as Professor Bergles often mentions in his papers and talks, is still valid in spite of great strides made in computer technology. Professor Bergles, however, pointed out, contradicting Mouromtseff that the analytical tools, and not cut-and-try methods, would become the favored design tools. In this paper, Professor Bergles skillfully takes the reader on a journey of electronic highways, passing through a densely packed thermal section.

Advanced cooling techniques are being constantly introduced in electronic packaging applications. In keeping pace with these developments, Bergles [162] presented a keynote address in which he described the additional developments - such as the thermal conduction module - taking place in the industrial world.

With the advancements in liquid cooling, Bergles [178] presented a comprehensive survey paper on liquid cooling of electronic equipment. The paper presents many milestones in the development of the liquid cooled systems, with details of some advanced systems (TCM, microscopic channels, and open bath cooling of MCMs).

Bergles [200] provides a good summary of high flux boiling systems as applied to microelectronic cooling. He discusses many issues related to pool and flow boiling systems. Nakayama and Bergles [218] present a comprehensive overview of microelectronic cooling in relation to advanced chip cooling systems.

Bergles and Bar-Cohen [262, 272] provide a detailed account of direct cooling of microelectronic components. They summarize the

historical development, and present detailed information on a number of advanced systems using liquid cooling approach. This should serve as a reference for researchers and industry engineers for any liquid cooling system development.

To improve the heat flux densities of microelectronic chips, Ma and Bergles [140, 166] studied boiling jet impingement cooling. R-113 jets were directed against simulated chips. They identified subcooled jets as the most promising way to cool the chips efficiently. Tien et al. [203] introduced nitrogen gas jets impinging on the chip surface submerged in a pool of liquid of low volatility (kerosene), with substantial enhancement in heat transfer rates. Ma and Bergles [219] further conducted experiments with R-113 systems and developed a theoretical model to predict the heat transfer in this two-phase two-component system.

Continuing further on the application of boiling to cooling of chips, Park and Bergles [163, 201] studied the effects of size on the heat transfer coefficient and CHF using simulated chips. They also studied effect of mounting - flush or protruding - on the heat transfer performance of the chips. The results were presented in a graph, and they also developed a correlation for predicting the CHF for different configurations. An interesting fact observed by them was the deactivation of cavities with decreasing heat flux, a phenomenon called by them reverse overshoot.

Another way of improving the performance further is to use enhanced pool boiling surfaces on the microelectronic chips in pool boiling with FC-88. Park and Bergles [168] studied the performance of simulated chips with four types of enhancements - microhole, microfin, Linde High Flux, and Thermoexcel-E. The temperature overshoot and the thermal performance with increasing and decreasing heat fluxes were compared for these surfaces. The High Flux surface provided the best performance overall.

Porous surfaces are used for enhancing pool boiling heat transfer. These surfaces are prepared from a sintering process. The sintering particle material, size, and the processing govern the structure of the sintered surface. Kim and Bergles [174] conducted an experimental study to investigate the effect of various parameters on the pool boiling performance in microelectronic application using R-113. Three sizes of copper particles were used. In the fourth sample, they employed three layers with different particle sizes. The performance of all surfaces was above the plain surface, but the overshoot still posed a problem.

Park and Bergles [177] employed heat sinks to enhance the heat transfer from chips immersed in liquids. Fins with holes and slots were used with R-113. They did not observe the typical temperature overshoot with these devices. The temperature overshoot problems were reduced by Bergles and Kim [202] by introducing an additional heater below the chip surface to provide the initial nucleation sites. Continuing with this work, Bergles et al. [234] developed porous surfaces by etching in-situ copper-niobium alloy. The copper matrix was preferentially etched away, and the surface was cold-rolled to provide re-entrant cavities. The temperature overshoot was considerably reduced with these surfaces.

Park et al. [220] studied the performance of simulated microelectronic chips with different fluorinert liquids. They also experimentally measured performance with different enhancement devices. This work is expected to lead into the development of optimized surfaces for different fluorinert liquids.

Carvalho and Bergles [245] conducted an experimental study to determine the effect of subcooling on nucleate boiling and CHF of simulated microelectronic chips. They tested several enhanced surfaces. They found subcooling to be ineffective in improving the performance at high heat fluxes. The CHF however increased with subcooling. Further research in this area is warranted to clarify some of the issues raised in this paper.

The more commonly employed natural convection heat transfer in cooling of electronic chips was studied by Park and Bergles [150, 176]. They used R-113 and water as the test fluids on simulated chips. The effect of width for small heaters was documented. The heat transfer coefficient increased with decreasing width, with the effect greater in R-113 than in water. This effect was incorporated in a correlation, the first of its kind, to predict the natural convection heat transfer coefficient for small heated surfaces. They also investigated effect of arrangement - in-line or staggered, and spacing between the heaters - for arrays of chips mounted on a vertical surface. They also noted that protruding heaters performed about 14 percent better than the corresponding flush heaters.

Cooling of multiple chips by natural convection poses additional problems due to interaction through the fluid stream flowing over them. Milanez and Bergles [167] studied the effect of a lower heater on the heat transfer from an upper heater. The lower heater enhances the flow of the fluid, but the fluid is also preheated. They measured the performance of two line heat sources simulating the electronic chips, and compared them against analytical solutions. This study addresses the practical problem encountered in designing electronic systems consisting of multiple heat sources, each with different thermal requirement and characteristics. This work was extended to the immersion cooling of multichip modules (MCMs) by Zitz and Bergles [274]. They developed a detailed computerized test system to monitor the vast amount of data generated by the MCM module in the entire range covering natural convection cooling, pool boiling, and CHF. The development of such advanced test facility is a result of a multiple series of works initiated by Professor Bergles and other team members on different aspects of immersion cooling.

## 2.7 HISTORY OF HEAT TRANSFER

Advancement of technology in various fields is a result of available tools and technological needs of the society at a given time. Scientists and inventors focus their energies in obtaining solutions to make a difference in the lives of people. Inventions of steam, gasoline, and diesel engines transformed the transportation scenario world-wide. The replacements were made in stages, to meet the perceived demands of the marketplace, without stepping ahead too much of the times, achieving a balance among the market forces.

Such developments have taken place in many different fields. The current computer revolution deserves an entire chapter in the technological history books.

Knowing the historical development stages in heat transfer technology is important to all of us, the heat transfer engineers. It gives us a sense of reference, and relevance, while deciding our future research directions. Professor Bergles over the years acted like a historian in search of original publications and major events related to heat transfer. He read the papers published in 1700s, 1800s and early 1900s carefully, and presented a concise summary removing some misconceptions that crept in the literature regarding the origins of many concepts and terms used currently in heat transfer practice.

In his keynote address in 1976, Bergles [77] presented some historical developments, dating from 1756, drawing from many sources, with authors like L. S. De Camp, K. J. Bell, A. F. Burstall, and E. S. Ferguson. With clear sketches and interesting photographs, he described the first steam engine (Heron's whirling aeolipile), Watt's single-acting steam engine, and Trevithick's locomotive.

The evolution in the cooling technology for electrical, electronic and microelectronic equipment deserves a special place in the history of heat transfer. Bergles [179] presented an excellent historical review, starting from Mourmstseff's work (1935, 1942) on water and forced-air cooling of vacuum tubes. He summarized London's analysis (1954) of a 25-kW tube, Kraus' work (1965) on liquid cooling of a high-power traveling-wave tube, and other novel methods introduced by Kaye, Chu, Hwang, Simons, Kilham and Ursch, Seely, Choi, Bar-Cohen, and Steinberg.

The enhancement of convective heat transfer has a history of its own, dating from the original paper by Newton (Principia, 1687), who introduced the idea of cooling laws, later put in a mathematical form and attributed to as Newton's law of cooling. Professor Bergles takes us through this historical journey with landmarks from Fourier (1822), Joule (1861), Mollier (1897), and the founder of "modern" heat transfer, Nusselt (1915). The "roots" of the enhanced heat transfer were discovered by Professor Bergles in the early work by Whitham (1896) on introduction of retarders (now called twisted tape inserts) in fire-tube boilers, by Lea (1921) who introduced spiral fins in the tubes to agitate oil in a water-cooled oil cooler, and by the Swedish inventor Forssblad (1928) who described novel configurations for plate-fin heat exchangers. He referred to the book by Royds (1921) which gives a good picture of heat transfer technology at that time. The works by Jakob and Fritz (1931) on enhanced boiling surfaces, and Tucker and Paris (1921), and Richards on the effect of sound waves on heat transfer were also visited.

The papers written by Professor Bergles on history of heat transfer have a special place in heat transfer literature. They serve as time capsules, preserving the major developments through time, and providing a background and history to give all heat transfer practitioners a sense of belonging to this long tradition of engineering practice.

### 3. CLOSURE

Engineering research has many facets, including: fundamental mechanisms, methods for improvement, experimental data, and models and correlations. Professor Bergles has exhibited a mastery in these areas, combining the science and art of research. When one looks at the breadth and the depth of the work done by him, it makes his achievements even more glorious. During his continuing academic career spanning over thirty years, he undertook a number of responsibilities, most of them simultaneously, including: conducting research, writing research papers, reports, and proposals, guiding M.S. and Ph.D. students, attending conferences, preparing for invited talks and short courses, teaching undergraduate and graduate courses, welcoming visitors, and spearheading the department or the college in the administrative responsibilities. Truly, he serves as a role model for all engineers, particularly those engaged in the field of research and education. We wish him well, and look forward to his continued guidance and leadership.

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