Artwork—A Review of Research Work Done by Professor Arthur (Art) E. Bergles

Professor Arthur E. Bergles has made major contributions in a number of areas in heat transfer. This article 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: (1) enhanced heat transfer, (2) two-phase flow and heat transfer, (3) heat transfer to refrigerants (boiling and condensation), (4) cooling of electronic components, (5) laminar internal flow, (6) review and general articles, and (7) history of heat transfer. This research, conducted over more than 30 years, has produced a wealth of high-quality experimental data, theoretical models, and 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. The present article presents a comprehensive survey of his research work.

The research work of Professor Bergles has been conducted during a span of over 30 years. Professor Bergles, through his extensive reports and publications, has played a major role in heat transfer research over several decades. He defined research needs through visionary review papers. Further, he identified the potential benefits of conducting fundamental and applied research work for industrial applications, especially in enhanced heat transfer. And finally, as a true researcher in his soul, he set out to obtain invaluable experimental data as well as insight into the underlying mechanisms governing related phenomena in numerous fundamental heat transfer problems.

The experiments conducted by Professor Bergles not only provide valuable data, they also bring out the importance of properly designing an experimental setup 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 first considered a list of alternatives, and then narrowed it down to specific configurations through broad experimental investigations. This was followed by 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 researchers in academia as well as in industry.

A list of research publications by Professor Bergles published through December 1996 is included under the list of references.* The articles are classified into 10 categories as shown in Table 1. The numbers in front of a category indicate the article reference numbers.

I am deeply indebted to Professor Bergles, who extended untiring support in preparing this article. He made his research articles available to me in well-organized form and helped me through his illuminating discussions and prompt responses. I would like to extend special thanks to Professor Bora B. Mikic at the Massachusetts Institute of Technology for his constant encouragement and many constructive comments. I sincerely appreciate his generous help.

This article is essentially similar to one published under the same title in *Process, Enhanced, and Multiphase Heat Transfer, A Festschrift for A. E. Bergles*, R. M. Manglik and A. D. Kraus (eds.), Begell House, New York, 1996.

*The list of references is in a slightly different format. Since there are many articles with the same authors in a given year of publication, the articles are numbered and are listed in chronological order. The articles are referenced by these numbers in the table and the text (within square brackets).

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

REVIEW OF RESEARCH IN SPECIFIC AREAS

Table 1 covers all 300 articles published by Professor Bergles until the end of 1996. The following review presents the highlights and some important details and relevance of his work. Due to space constraints, all the articles listed in Table 1 could not be discussed. Although figures and tables are not included here, the readers can identify the relevant articles from the information presented here, and then refer to those articles for additional details.

Enhanced Heat Transfer

Professor Bergles has been one of the most active proponents of enhanced surfaces in heat transfer applications. He has displayed vision in recognizing the importance of enhancement in refrigeration, power, process, and microelectronic cooling applications. In his 1979 article 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 article, "Commercialization represents the ultimate stage of development; however, even commercial products require additional development work." He was among the first to address comprehensively 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 that 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.

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% 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. The authors provided experimental results in 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 affect the fluid flow field and the associated heat transfer process directly. 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 article 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%, 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 8–17%, for perfect contact between the tape and the wall. For a constant pumping power, twisted-tape inserts provided a 20% 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 the highly nonlinear 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 1,000% increase, as compared to plain empty tubes. However, the pressure drop penalty was extremely high, up to 20 times higher in certain cases.

Internally finned tubes are another form of enhancement technique tested extensively by Professor Bergles (Bergles et al. [36]). The heat transfer performance of eight internally finned tubes was obtained experimentally 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 25–170% for a given pumping power.

The twisted tapes were tested for augmentation in the laminar flow region (Hong and Bergles [64]), where a 1,000% 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 1,260–8,130) by Marner and Bergles [147]. It was found that the internally finned tubes yielded a 400% increase in heat transfer coefficient for heating, while the twisted-tape inserts were more effective for the cooling applications, yielding 150–225% 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 articles (Marner and Bergles [231]; Manglik and Bergles [261]), in which extensive experimental data on heat transfer and pressure drop were reported.

The available experimental data for water, ethylene glycol, and Polybutene 20 obtained in earlier studies were correlated within ±25% (Manglik and Bergles [182]). However, this correlation covered a limited range of parameters. In subsequent articles, 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, tube-side enhancement of the heat transfer coefficient could result in considerable savings in 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 spirally grooved tubes with an overall average error of less than 10% with the existing data. This represents one of the most comprehensive correlation schemes that accounts for the geometric factors and fluid characteristics. One of the benefits of this correlation is that it is possible to see clearly the parametric influences of different geometric parameters on the performance. It also serves as a valuable tool to the designer who is faced with the selection of an optimum geometry based on not only the thermal, but also economic and manufacturing constraints.

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%, 157%, and 65% over a plain empty tube, while the corresponding increases in pressure drop were 1,100%, 1,000%, and 160% 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% 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% at a Reynolds number of 10,000, with corresponding pressure drop increases of 400% to 1,800%. 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 appears to increase the heat transfer coefficient, but 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 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 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 at the wall during a transient conduction process. The correlation scheme incorporates a constant that is characteristic of the individual insert.

Raviguruajan 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 ribbed geometries.

Twisted-Tape Inserts with Non-Newtonian Fluids. Non-Newtonian fluids are often encountered in the 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 pseudo-plastics. The three basic mechanisms of augmentation, (1) secondary flow effects, (2) an increased flow path, and (3) 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% of HEMC solution in a 12.85-mm-diameter stainless steel tube. They attributed the increase in heat transfer coefficient with pseudo-plastics in single-phase flow to (1) the non-Newtonian effects, and (2) 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 ±30%. This is quite remarkable, considering that Hong and Bergles [64] could predict their own water and ethylene glycol data only to within ±25%. Similar treatment resulted in a reasonable agreement with pressure drop data as well (+25% to −30%.)

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 the applicability of natural convection 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 the 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 the 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 × 178-mm aluminum plate. A Mach-Zehnder interferometer was used for taking local measurements. The effects of pitch, height, and width (in the case of ribs) were investigated. It was found that the transverse ribs, in fact, decrease the overall heat transfer rate by creating stagnation zones on both the upstream and downstream sides of the ribs. The stepped surfaces helped to improve the performance. Bhavnani and Bergles [213, 252] studied the effect of a sinusoidal wavy surface on heat transfer. This geometry resulted in average heat transfer rates very close to plain-surface values. An effect of wave amplitude was seen in the results. Smaller amplitudes caused the transition to turbulence at lower Grashof number values of around 2×10^7 as compared to a plain vertical surface. It was found that if the lower edge of the plate was curved inside, this 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, roped or corrugated, helical fins, axial fins, and helical rib roughness. They conducted the tests with magnesium oxide (approximately 3 μm diameter) as the foulant suspended in distilled water. The tests showed that 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 roped or corrugated tubes showed a remarkably lower fouling rate. However, Bergles [273, 278] reported a review of other work 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 the 1960s and 1970s. Bergles [19] presented a comprehensive survey of different augmentation techniques, and identified the need to establish generally applicable selection criteria for augmentative techniques. 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 article, Bergles et al. [45] proposed 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 increased heat transfer, reduced pumping power, and reduced heat exchanger size. With these parameters, the following eight criteria were proposed: (1) for fixed geometry and flow rate, increased heat transfer; (2) for fixed geometry and pressure drop, increased heat transfer; (3) for fixed geometry and pumping power, increased heat transfer; (4) for fixed geometry and heat duty, reduced pumping power; (5) for fixed heat duty and pumping power, reduced exchanger size; (6) for fixed heat duty and pressure drop, reduced exchanger size; (7) for fixed heat duty and flow rate, reduced exchanger size; and (8) for fixed heat duty, flow rate, and pressure drop, reduced exchanger size. Bergles et al. 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 the 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 5,000 to 30,000 under a constant-pumping-power constraint, while the range drops to between 3,000 to 5,000 under the constant-pressure-drop constraint.

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 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 subcooling. Burn-out heat fluxes were not significantly altered with 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 from the 1940s. New surfaces with porous coatings and modified low-finned tubes were manufactured commercially under 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% and 60%, 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. Ayub and Bergles 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 filling 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, when 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] presented a study focusing on the hysteresis effect of structured surfaces in pool boiling. They showed that tubes coated externally with porous metallic coatings showed considerable nucleate boiling enhancement once 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] discussed 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 were discussed by Bergles [215] in a comprehensive article 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 by 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. They 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 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. These authors 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 to develop better correlating schemes for mixtures with enhanced surfaces was identified.

Enhancement in Two-Phase Flow, Boiling, and Condensation

There is a need to improve the performance of heat transfer equipment incorporating boiling and condensation processes from an energy conservation viewpoint. The benefits to the refrigeration, power, and process industries would result directly from the overall conservation of energy resources. With the rapid advancements in 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 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 the thermal performance by extending the laminar film condensation theory. Although the experiments yielded lower heat transfer rates than predicted by the theory, a number of practical problems arising in such research work were pointed out. These include proper degassing procedure the effect of noncondensables, and the assumption of nonuniform 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 many investigators studied condensation enhancement techniques, Professor Bergles pointed out that very few efforts were directed toward 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%, while the internally finned tubes showed an improvement of 300%, 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, the density ratio of the two phase, and the wall shear stress. Twisted tapes were seen as possible retrofit devices in existing condensers.

Wall roughness elements, such as helical repeated ribs and spirally fluted tubes, were found to be effective in enhancing single-phase heat transfer. Professor Bergles investigated their performance for in-tube condensation. Luu and Bergles [114] and Bergles [139] reported that their experimental study of helical repeated ribs and spirally fluted elements yielded 80% and 50% enhancement in heat transfer coefficient over a smooth tube. Correlations for these geometries were proposed.

The use of microfin tubes for condensation applications was studied extensively 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 were improved considerably over those for 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 effects of fin shape, fin height, number of fins, and spiral angle were discussed. This information proved useful to manufacturers in the design of new and more efficient microfin geometries.

Microfin tubes were at that time being introduced in the refrigeration industry, and with 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 results clearly identified the tube that 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 electrically heated and fluid heated test sections during evaporation of refrigerant R-113 in smooth and microfin tubes. The heat transfer coefficient was the same for the two cases at low and medium mass flow rates; however, the high mass flux rates, the electrically heated long test section gave 20–40% 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 microfin tubes with a helix angle around 16–18° 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 applications. 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. Khanpara et al. 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 20–40%. The effect of tube diameter on the performance was insignificant. This work showed that a microfin geometry could be applied to different-diameter tubes without any modifications. These studies clearly indicated the superior performance of microfin tubes in boiling and condensation. It is therefore no surprise to see their widespread use in the refrigeration and air-conditioning industries.

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

In practical applications, a small amount of oil is generally present in the evaporators and condensers of a refrigeration system. Schlager et al. [204] present a detailed study of 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% led to an improvement in the evaporative heat transfer coefficient for smooth tubes, but the low-fin tube showed very little enhancement. Larger quantities of oil degraded the evaporator performance for the low-fin tube below the smooth-tube level. The condensation performance was degraded with the presence of oil, but it was less adversely affected compared to smooth tubes. The work showed clearly 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 codensation 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 exhibited similar trends, although the enhancement was less. The condensation heat transfer coefficient decreased with an increase in oil concentration for both tubes. Schlager et al. [209] 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 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 for the finned tubes were similar to those for the microfin tubes, but were consistently below those for 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 designers of heat transfer equipment.

The mechanisms responsible for degradation of heat transfer performance in microfin tubes with oil were not clearly understood, so 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% enhancement is possible with the introduction of a swirl generator in the flow. In this work, Professor Bergles also considered the practicality of the enhancement device by studying its performance under a given pressure drop or pumping power condition. Assuming that swirl flow promotes thermal equilibrium in 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 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.

Enhancement with structured surfaces in falling-film evaporators was investigated by Chyu and Bergles [148, 232]. The surfaces tested included a 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 to investigate structured surfaces with different fluids for specific applications.

Review Articles on Enhanced Heat Transfer

One of the most significant contributions to the technical community made by Professor Bergles is in providing state-of-the-art reports in many areas, including enhanced heat transfer. He started his work in this area in the early 1960s, and is still in the midst of publishing various review articles.

Professor Bergles' first elaborate review article on augmentation techniques appeared in 1969 (Bergles [19]). He referenced 371 articles in this work, and classified them into the following categories: vortex flows, including twisted-tape swirl generators; vibration of the heater surface; electrostatic fields; and various types of additives. Nonboiling, boiling, and condensation in free and forced convection, and mass transfer in forced convection were covered. The review included key information from various articles, and offered guidance for practical applications by presenting turbulence promoter data in terms of a pumping power performance criterion. Professor Bergles reported important experimental data in figures, which were carefully drawn to include detailed information on the experimental conditions for which the results were presented. He compiled and presented the experimental investigations in tabular form to bring out clearly their key features. Through this article, Professor Bergles raised the standard for presenting state-of-the-art reviews, and he himself wrote more than 50 such in-depth reviews on different aspects of heat transfer.

To aid researchers in narrowing their search to specific articles, and to help designers find specific references in their field of interest, Professor Bergles started preparing a bibliography of available literature on various topics. Bergles and Webb [35] presented the first such bibliography on augmentation of convective heat transfer. It included references to 472 articles. Professor Bergles then developed an extensive bibliographic collection, resulting in a six-part series co-authored 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 on-line computer services, the exhaustive bibliographic collections, presented under specific categories, are a valuable resource for researchers and designers, since a computerized search is able to capture only a fraction of the available literature.

Professor Bergles kept pace with developments in enhanced heat transfer, and provided critical surveys, that were valuable in determining the potential of a given augmentation technique for a specific application. He has constantly updated his reviews on augmentation, and has published them periodically since 1969. Reviewing the augmentation of convective heat transfer, he has authored or co-authored the following articles: Bergles et al. [49], [52], [66], [84], [88], [89], [109], [110], [111], [132], [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 has been directed toward enhancement in boiling and condensation applications. He presented his first article in this area, Bergles [74], in 1976, and has steadily reported his latest compilation of research work: [78], [134], [142], and [229].

Professor Bergles presented extensive review articles 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 reviews, 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 the last 20 years or so as second-generation heat transfer technology. Starting with the smooth tube as the first generation, finned surfaces and 2-D structured surfaces are classified as second-generation enhancement technology. Starting in 1983, Professor Bergles has extensively reviewed the second-generation enhancement devices in the following articles: 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 articles 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 were invented many years ago, their widespread acceptance in industrial applications really determines their "age."

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 circumferential variation in the wall temperature by considering two limiting tube-wall conditions—an infinite-conductivity tube, and a 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 and 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 × 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. In a later technical note, Professor Bergles [34] 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 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 graphical form, covered both the developing and the fully developed flow regions. The heat transfer results were much higher (about three 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 showed 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, rather than a viscosity correction factor, was employed to account for the property variations. Hong and Bergles [69] presented analytical solutions for 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% above the results for the constant-property solution.

To gain 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] presented analytical solutions for developing and developed flows, and showed that the heat transfer rate is increased by 200% 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 articles by Professor Bergles on enhancement in the laminar region are summarized in a later section.

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 enhanced tubes (especially microfin tubes) for boiling and condensation is noteworthy, and is covered above. In this section, his work on other aspects of heat transfer to refrigerants is discussed.

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 the refrigerant, and is carried over from the compressor to the condenser and evaporator. Baustian et al. [158] reported 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 density, viscosity, and acoustic velocity, respectively. These devices provided practical solutions to 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 microfin tubes. The presence of oil caused foaming, which wetted the walls, and led to foamy slugs in the evaporator. This explains the improvement in the heat transfer coefficient for smooth tubes with the addition of oil to pure refrigerants. Since the wetting phenomenon is already present in microfin tubes, the presence of oil does not necessarily improve the heat transfer. Further, Manwell and Bergles 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 concentrations in the evaporator and condenser play 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 above, 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%. In runs with clearly separated flow, the heat transfer coefficient at the base was three to five times higher than the average value. The importance of liquid film for evaporation was 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] presented a valuable discussion of 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 article provides valuable insight into 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.

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.

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 used in 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 used in nuclear steam generator applications. Bergles [26] investigated two-phase flow structure visualization with high-pressure water in a rod bundle, and found significant differences in flow patterns in different subchannels. Using an 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 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 two-phase critical flow under diabatic conditions, which is relevant in studying 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 flow rate.

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 the 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.

Instrumentation in Two-Phase Flow

Professor Bergles refined the art of experimentation by using many new instrumentation techniques. In one of his articles, 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 a more satisfactory discrimination between the two phases. Carvalho and Bergles [254] also found the optimal sensor temperature corresponding to 60°C, which was much higher than those reported in earlier studies.

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] studied experimentally 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 (1,000 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.

Subcooled Flow Boiling Heat Transfer

As one of his first articles, Professor Bergles presented an often-referenced article on 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 given superheat and flow conditions. Also, the heat transfer rates in the region between forced convection and fully developed boiling was 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 Dormer [18] conducted extensive experiments to study the pressure drop in subcooled boiling of low-pressure water in 2.5. to 4.0-mm-diameter tubes. The pressure drop data were then correlated in chart form, and curves were presented to cover the entire range of data. This was one of the first studies in this area. The information is useful in studying the 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 is 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 a "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 μm) 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 article 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 Dormer [18] was extended with 1.05- to 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 tube diameter. Tong et al. [294] developed a pressure drop correlation that is particularly useful in designing cooling systems to accommodate high heat fluxes.

Flow Boiling Heat Transfer in Enhanced Tubes

Flow boiling heat transfer in enhanced tubes is covered earlier, in the section on enhanced heat transfer.

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

Professor Bergles 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 experimental data and photographic information about 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 of possible mechanisms leading to CHF based on the information from a Fastax (1,200 frames/s) camera and microflash photos.

Bergles [60, 72] surveyed the available literature and provided comprehensive coverage of the description of the burnout phenomenon in pool boiling with different heater configurations, and different CHF augmentation techniques. This article presents a useful summary, and more important, future directions for researchers. Similar reports were presented by Bergles [73] for low-quality forced-convection systems, and by Bergles [100] for high-qualtiy forced-convection systems. These comprehensive surveys provide a clear picture of the parametric trends and effects of important system variables on CHF. For pool boiling systems, Park and Bergles [195] collected 2,237 data points for CHF and fitted polynomial curves 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 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 more efficient heat transfer under the restriction. Jensen et al. [70] attributed this increase to 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^2 s, and subcoolings ranged from 40 to 135°C. In some preliminary tests, a maximum heat flux of around 10^8 W/m^2 was achieved. The CHF was shown to increase with both velocity and subcooling. Small-diameter tubes provided 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 was able to correlate the CHF data well. Carvalho and Bergles [259] verified a new parameter, "conpacitance," 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%.

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 the CHF was deemed necessary to clarify the situation for flat heaters, which forms the basis for other geometries as well.

CHF in Helically Coiled Tubes

Helically coiled tubes are used in industries for single-phase, evaporating and condensing flows, and many other applications. At 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 nondimensionalized radial acceleration was able to account for CHF in helically coiled tubes. The CHF in these tubes was lower than in 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 that receives 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 by 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 nonuniform circumferential heating is of interest in nuclear applications as well.

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 undergraduate education, as is clearly seen in his publication dealing with laboratory experiments demonstrating 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 researchers in tune with the needs of the industrial community. In one of his early articles, Bergles [96] presented such a link by indicating future needs in two-phase flow research. Multibeam X-rays, rotating heat pipes, OTEC power plants, and pressurized-water reactors (PWRs) were the examples he used in identifying 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, postdryout, and quenching. The quenching phenomenon is of interest in reactor cooling under accident conditions. Additional effects due to the transient nature of the process make it different than that described by the steady-state pool boiling curve.

Continuing in the area of nuclear thermal hydraulics, Bergles [132] presented a comprehensive picture of the heat transfer-related issues related to PWRs, and boiling-water reactors (BWRs). The specific issues related to boiling heat transfer were then dicussed in further detail. Bergles [144] provided 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 articles are published every year. It is therefore very difficult for design engineers of two-phase heat exchangers to keep track of the 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. This article 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] provided similar information on boiling heat transfer pertaining to a single tube in a large pool, and single vertical tube. This work provided a basis for studying boiling in other, more complex geometries, such as rod bundles and multiple vertical channels.

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 air cooling would continue to be used 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 the 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 an article on the evolution of cooling technology for electrical equipment and electronic devices. He quoted Mouromtseff in his 1942 article 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 articles and talks, is still valid in spite of great strides made in computer technology. Professor Bergles, pointed out, however, contradicting Mouromtseff, that the analytical tools, and not cut-and-try methods, would become the favored design tools. In this article, Professor Bergles skillfully took 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 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 on liquid cooling of electronic equipment. The article presents many milestones in the development of liquid-cooled systems, with details of some advanced systems (Thermal Conduction Module, microscopic channels, and open bath cooling of multichip modules).

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

Bergles and Bar-Cohen [262, 272] provided a detailed account of direct cooling of microelectronic components. They summarized the historical development, and presented detailed information on a number of advanced systems using the 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. Ma and Bergles identified subcooled jets as the most promising way to cool the chips efficiently. Tien et al. [203] introduced nitrogen gas jets impinging on a 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 with 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 the effect of the 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 they called "reverse overshoot."

Another way of improving performance is to use enhanced pool boiling surfaces on microelectronic chips in pool boiling with FC-88. Park and Bergles [168] studied the performance of simulated chips with four types of enhancements: microholes, microfins, 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 pool boiling performance in microelectronic applications using R-113. Three sizes of copper particles were used. In the fourth sample, the authors 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. Park and Bergles 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 reentrant 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 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 article.

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 being 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. Park and Bergles also investigated the 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% 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 a 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. Zitz and Bergles [274] extended this work to the immersion cooling of multichip modules (MCMs). 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 an 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.

History of Heat Transfer

Advancement of technology in various fields is a result of available tools and the technological needs of the society at a given time. Scientists and inventors focus their energies on obtaining solutions to make a difference in the lives of people. The inventions of steam, gasoline, and diesel engines transformed the transportation scenario worldwide. 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 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 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 articles published in the 1700s, 1800s, and early 1900s carefully, and presented concise summaries, removing some misconceptions that had crept into 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, including authors such as 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 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 Mouromtseff's work (1935, 1942) on water and forced-air cooling of vacuum tubes. He summarized London's (1954) analysis of a 25-kW tube, Kraus's (1965) work 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 article by Newton (*Principia*, 1687), who introduced the idea of cooling laws, later put into mathematical form and attributed as Newton's law of cooling. Professor Bergles took 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 enhanced heat transfer were discovered by Professor Bergles in early work by Whitham (1896) on the 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. Professor Bergles referred to a book by Royds (1921), which gives a good picture of heat transfer technology at that time. The work of Jakob and Fritz (1931) on enhanced boiling surfaces, and of Tucker and Paris (1921), and Richards on the effect of sound waves on heat transfer, were also visited.

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

CLOSURE

Engineering research has many facets, including fundamental mechanisms, methods for improvement, experimental data, and models and correlations. Professor Bergles has exhibited mastery in all these areas, combining science and the art of research. When one looks at the breadth and depth of the work done by him, it makes his achievements even more glorious. During his continuing academic career spanning over 30 years, he undertook a number of responsibilities, most of them simultaneously, including conducting research, writing research articles 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 administrative responsibilities. Truly, he serves as a role model for all engineers, particularly those engaged in the fields of research and education. His research articles and continued interaction with the heat transfer community will undoubtedly inspire many of us to continue this great tradition of fundamental as well as applied heat transfer research.

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