Historical Developments in the Research of Boiling Heat Transfer*

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In former years the boiling phenomenon had been considered to be natural and self-evident. Prior to 1930, boiling liquids were studied by only a few researchers. An abrupt change has been brought about by new engineering challenges, i.e. high power density systems such as nuclear reactors, rocket engines and spacecraft. Furthermore, research into the boiling phenomenon has become active recently in relation to the development of new forms of the energy and the energy conservation. It is appropriate to review the historical developments in boiling heat transfer that have led to the present status of understanding. The five decades of modern progress, from 1930 to the present, are described with particular attention to the feature most prominent in each decade in relation to various fields of boiling; pool boiling, flow boiling and supercritical fluids. Furthermore, the development of steam power (including nuclear power) and the technology of energy conservation are considered, corresponding to the progress of boiling research.

Key Words: Phase Change, Boiling, Supercritical Fluids, Heat Transfer, Steam Power, Energy Conservation, History.

1. Introduction

The boiling phenomenon is one of the most familiar phenomena in daily life and is the mode of heat transfer known since old times. Man's acquaintance with this must be as old as the discovery of fire. As the mankind became familiar with boiling so early, boiling was thought of as being most natural and self-evident, and therefore the study of boiling liquids received little attention from engineers until recently. The commencement of substantial study into boiling heat transfer was made in 1930, and since 1950 the study of boiling heat transfer has become more and more active, and now it is so active that it occupies the greater part of the field of heat transfer research⁽¹⁾. The advent of high power density systems such as nuclear reactors, rocket engines and spacecraft gave a great impetus to research into boiling heat transfer.

Although the effort in terms of man-hours and expenditure has been very substantial indeed, the results have not been entirely satisfactory. In this paper the historical developments of research into boiling heat transfer are reviewed, and possible orientations for future advancement are proposed.

2. Early History and Recent Trends of Boiling Research

The first scientific study of boiling may perhaps be that of the Leidenfrost phenomenon (1756)⁽²⁾. This phenomenon is the occurrence of a repulsion between a liquid and a very hot solid. A drop of water on a hot plate will dance around noisily for some time before evaporating. On a moderately warm plate the phenomenon does not appear and evaporation is very rapid. On the other hand, metallurgists have long known that hot metals seem to cool in two steps when quenched⁽³⁾. At first, the rate of cooling is very slow, in spite of the high temperature of the metal; and later, the rate is rapid, although the temperature of the metal is much lower. The explanation of these facts

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was not possible until Nukiyama carried out his classical experiments. Until 1930, only these sporadic studies were carried out. The systematic study of nucleate boiling was first carried out by Jakob in 1931.

The research into boiling heat transfer has made rapid progress over the last thirty years. This trend still continues at present, judging from the number of published papers. However, its qualitative progress has stagnant in some way, showing a descending tendency also quantitatively after the golden age of the 1960's. Very recently, the boiling studies have shown an ascending tendency again, in connection with the efficient use of thermal energy, and are becoming active with the promotion of energy conservation technology and the progress of the technology of cryogenic engineering.

Figure 1 is a summary of the references to boiling published until 1965 by Gouse⁽⁴⁾. It can be seen that 1930 is essentially the starting point on boiling research, and that the total number of references until 1950 has doubled every ten years, and since 1950 this doubling period has been reduced to five years.

3. Research Trends in Each Field of Boiling

Table 1 shows the major references relating to boiling heat transfer arranged in order of the year of publication. In this figure the brackets ( ), < >, [ ], { }, < > and { } show the references for

Fig. 1 Number of publications on two-phase gas-liquid flow phenomena appearing per year versus the year of publication, to 1965 (Gouse, 1966)

nucleate boiling, transition boiling, film boiling, boiling characteristic curve, forced convection, critical heat flux and free convection respectively, and the letters in the brackets refer to the author's names.

The first column in Table 1 refers to pool boiling. A series of investigations of nucleate boiling by Jakob since 1931, and the famous experiment with wire by Nukiyama in 1934, can be said to be the pioneering research into boiling. From 1931 to 1950, researches to obtain the boiling characteristic curve by measuring the coefficient of boiling heat transfer were carried out sporadically.

Figure 2 shows the behavior which results from increasing the number of bubble population sites by increasing the heat flux (q) in the nucleate boiling of water by using the horizontal circular plate (diameter: 10 cm) as the heating surface, as demonstrated by Jakob⁽⁵⁾. Jakob clarified the influence of surface roughness, the history of the operation for heat flux i.e. the non-reproducibility of boiling, the effect of surface orientation, the diameter of the bubble just leaving the heating surface, the relation between the departing bubble diameter and the frequency of bubble formation, and so on.

Figure 3 shows the boiling characteristic curve obtained by Nukiyama⁽⁶⁾ by using platinum wire (diameter = 0.14 mm) in atmospheric water. In this

Fig. 2 The nucleation sites on the smooth heating surface for various heat fluxes in nucleate boiling of water (Jakob-Fritz, 1931)

Fig. 3 The boiling characteristic curve of water obtained by Nukiyama (Nukiyama, 1934)

Table 1 Chronological table of major references relating to boiling heat transfer

A. D.	Pool Boiling	Flow Boiling	Supercritical Fluids
1930	— (Jakob-Fritz)	—	( ) : Nucleate Boiling
	— (Cryder-Gilland)	—	< > : Transition Boiling
	— [Nukiyama]	—	[ ] : Film Boiling
35	— (Jakob-Linke)	—	[ ] : Boiling Curve
	— (Jakob) (Fritz-Ende)	—	( ) : Forced Convection
	—	—	< > : Critical Heat Flux
	—	—	( ) : Free Convection
1940	— (Insinger-Bliss)	—	
	— (Bonilla-Perry)	—	
	—	—	
45	— (Cicelli-Bonilla)	—	
	— [Farber-Scorah]	—	
1950	— [Bromley]	— (McAdams et al)	
	— (Rohsenow-Clark)	— (Buchberg et al) (Gunther)	
	— (Rohsenow) (Kutateladze)	— (Jens-Lottes)	
	— (Forster-Zuber) (Ellion)	— (Clark-Rohsenow)	
55	— (Westwater-Santangelo) (Yamagata et al)	— (Dengler-Addoms)	
	— (Nishikawa) (Rohsenow-Griffith)	—	
	— (Bankoff) (Zuber) [Hsu-Westwater]	— (Gambill-Green)	— (Dickinson-Welch)
	— (Gaertner-Westwater) (Levy)	— (Zenkevich) (Lottes-Petrich-Marchaterre)	— (Styrikowitsch-Milopolsky-Shitzman)
	— (Bankoff-Mikesell) (Forster-Greif)	—	
1960	— (Kurihara-Myers)	— (Griffith-Wallis) (Bell)	
	— (Nishikawa-Yamagata) (Berenson)	—	
	— (Moore-Mesler) (Hsu-Graham)	— (Collier et al)	— (Petukov et al) (Goldmann)
	— (Hughmark) (Isshiki-Tamaki)	— (Janssen-Levy)	
	— [Koh] [Sparrow-Cess]	— (Shrock-Grossman)	
	— (Zuber) (Séméria) (Stephan)	— (Swenson-Carver-Szoeke)	
	— (Moissis-Berenson) (Cole-Shulman)	— (Macbeth) (Tong) (Barnett)	— (Fritsch-Grosh) (Shitsman)
	— (Bergles-Rohsenow) (Sharp) (Merte-Clark)	— (Hewitt)	
	— (Siegel-Keschock)	— (Hewitt et al)	— (Nishikawa-Miyabe)
65	— (Geartner)	— (Bertoletti et al)	
	— (Marto-Rohsenow) (van Strahlen) (Nishikawa)	— (Macbeth)	— (Knapp-Sabersky)
	— [Nishikawa-Ito] [Ito-Nishikawa]	—	
	— (Kusuda-Nishikawa)	— (Bennett)	— (Grigull-Abazic)
	— (Lippert-Dougal) (Katto-Yokoya)	—	— (Goldstein-Aung)
	— (Cooper-Lloyd) (Ishibashi-Nishikawa)	— (Herkenrath-Mörkenstein)	— (Nishikawa-Ito)
	— (Bergles)	—	
1970	— (Mikic-Rohsenow) (Czikk-Gottzmann et al)	— (Hewitt-Kearsey-Collier)	— (Ackerman)
	— (Honda-Nishikawa)	— (Collier) (Tong)	— (Yamagata-Nishikawa-Hasegawa)
	— [Nishikawa-Ito-Kuroki-Matsumoto]	— (Nishikawa-Fujii-Yoshida)	
	— (Gottzmann-O'neil-Minton)	—	— (Nishikawa-Ito-Yamashita)
75	—	—	
	— (Nishikawa-Fujita)	— (Groeneveld-Delmore)	
	— (Arai-Fukushima-Nakajima-Fujie-Nakayama)	—	
	—	— (Katto)	
	—	— (Shah)	
1980	— (Stephan-Abdelsalam) (Nishikawa-Ito)	— (Katto)	
	— (Bergles)	—	
	— (Cooper) (Witte-Lienhart)	—	
	— (Nishikawa-Fujita-Ohta)	—	
	— (Nishikawa) (Webb) (Haramura-Katto)	—	
	—	— (Katto)	

experiment, two types of wire temperature jump have been recognized. From this fact it was concluded that at least two types of boiling occur. Furthermore, Nukiyama guessed that a third type should exist, which he sketched in a dotted line as shown in Fig. 3. This was a bold guess, because the reality of the dotted region would mean the existence of an undiscovered type of boiling for which an increase in the metal temperature causes a decrease in the heat flux. Such a slow-down with increasing potential does not occur with other transport phenomena. Later workers proved that Nukiyama was correct.

The period from the 1950's to the 1960's was the golden age of the research of pool boiling, and the active studies were carried out quantitatively and qualitatively. It is noteworthy that research for clarifying the mechanism of boiling heat transfer, such as the stability of nucleation (Bankoff), the growth of the vapor bubble (Forster-Zuber, Bankoff-Mikesell, Cole-Shulman, Mikic-Rohsenow), the stirring effect of bubbles (Rohsenow-Clark, Yamagata et al, Nishikawa, Forster-Greif, Isshiki-Tamaki), bubble population density (Yamagata et al, Westwater-Santangelo, Gaertner-Westwater, Kurihara-Myers, Gaertner), the microlayer theory (Moore-Mesler, Sharp, Cooper-Lloyd, Cooper) and the thickness of boundary layer (Yamagata et al, Hsu-Graham, Lippert-Dougall), has been carried out in parallel with the proposal of the correlation of nucleate boiling heat transfer (Rohsenow, Kutateladze, Nishikawa-Yamagata).

In nucleate boiling, the heat flux is not a single-valued function of the temperature; it depends also on the condition of the surface, because the bubble population is greatly affected by these conditions. Therefore the two-parameter expression of heat flux (q) in terms of bubble population density (N/A) and of the temperature difference (ΔT) is considered. Figure 4 shows an example of the experimental results for the atmospheric boiling water on the level of lower heat flux on the horizontal surfaces with artificial grooves by Nishikawa⁽⁷⁾, where h_m represents the average depth of the groove as the measure of roughness. The two-parameter expression approximates the data

Fig. 4 The two-parameter expression for heat flux in nucleate boiling of water

well. The bubble population density is the decisive factor governing the nucleate boiling heat transfer, and the problem of non-reproducibility in nucleate boiling can be clarified by introducing this concept.

In addition, the research into nucleate boiling under special conditions, such as the effect of gravity (Siegel-Keshock, Merte-Clark), the boiling of mixtures (van Stralen), the boiling in the liquid film (Kusuda-Nishikawa), the boiling in a confined space (Ishibashi-Nishikawa) and so on, were carried out. Furthermore, the boiling-like phenomena at the supercritical pressure (Goldmann, Nishikawa-Miyabe, Knapp-Sabersky, Grigull-Abadzic, Goldstein-Aung, Nishikawa-Ito) were investigated. Figure 5 shows an example of the behavior of convective flow for carbon dioxide at an almost critical pressure (the heating surface is horizontal platinum wire, 0.2 mm in diameter), and the boiling-like phenomena in the critical region where the difference between liquid and vapor vanishes in thermodynamical equilibrium, are recognized⁽⁸⁾.

(a) nucleate boiling-like phenomenon

(b) film boiling-like phenomenon

Fig. 5 Behavior of convective flow of carbon dioxide under almost critical pressure

After the golden age, research into boiling tended to slow-down gradually, but became active again after the 1970's. This was due to the increase of research intended to augment heat transfer in relation to energy conservation. Figure 6 shows a summary of the references to heat transfer augmentation published until early 1979 by Bergles⁽⁹⁾, and it is seen that research for this purpose has recently become active. Figure 7(a) and (b) show the comparison of boiling heat transfer performances in various prepared surfaces for R-113 and for water respectively. HIGH FLUX and THERMOEXCEL in these figures are the high performance boiling surfaces developed by Union Carbide in the U. S. A. and HITACHI and HITACHI CABLE in Japan respectively. The former is a novel boiling surface consisting of a porous metallic matrix which is bonded to a metallic substrate; and the latter is a machine roughened surface which has the circumferential tunnels with openings. And Br-350-0.94 represents the sintered surface with spherical bronze particles developed by Nishikawa-Ito⁽¹⁰⁾. It is seen from these figures that the effectiveness of these prepared surfaces varies with the wettability of the boiling liquids.

Referring to transition boiling, Ellion was the first to realize transition boiling by the temperature-controlled heating method. Since 1960 research into transition boiling has become active and the problem of stability in transition boiling (Zuber, Berenson, Moissis-Berenson), the analysis of solid-liquid contact phenomena (Westwater-Santangelo, Berenson, Honda-Nishikawa), the multiple characteristics of transition boiling (Nishikawa, Witte-Lienhart) and the proposal of a model for the heat transfer mecha-

nism (Honda-Nishikawa, Katto-Yokoya) have been studied.

As for film boiling, little progress had been made until 1960, except for the research by Bromley in 1950. Since 1960, research in this branch has become active due to the progress in cryogenic engineering, followed by space development, the cooling technique for superconducting magnets, and the development of the new type of nuclear reactor. The two-phase boundary layer theory (Koh, Sparrow-Cess, Nishikawa-Ito, Ito-Nishikawa) and the correlation of heat transfer for a vertical surface (Hsu-Westwater), a horizontal upward surface (Berenson) and a horizontal cylinder (Nishikawa-Ito-Matsumoto), were studied. Research into film boiling is becoming active lately in connec-

Fig. 6 References of heat transfer augmentation versus year of publication, to early 1979 (Bergles, 1981)

Fig. 7 Comparison of boiling heat transfer performance in various prepared surfaces

tion with cooling at flooding, and spray cooling in nuclear reactors and the cryogenic engineering.

The second column in Table 1 refers to flow boiling⁽¹¹⁾. The research of flow boiling was first carried out in the 1950's. In Japan, this kind of research was begun later than in the rest of the world; but now, the research in Japan is leading that in the rest of the world. It is no exaggeration to say that, especially the research of critical heat flux in Japan excels the level of that in the world.

Figure 8 shows the correlation of subcooled nucleate boiling by McAdams et al. It has been clarified that the effects of subcooling and velocity do not affect the boiling curve to a significant extent by plotting the heat flux (q) against the difference between the temperature of the heating surface (t_w) and the saturation temperature of the liquid (t_{sat}) i.e. the degree of superheat (Δt_{sat}). Referring to the forced convection boiling heat transfer, the correlations of subcooled boiling (Jens-Lottes) and of saturated boiling in the region of two-phase forced convection (Dengler - Addoms, Schrock - Grossman) were proposed in the period from the 1950's to the 1960's. Furthermore, it is a peculiarity of the 1960's that the research of heat transfer to supercritical fluids had been carried out actively because of the requirements of industry, such as practical applications to supercritical pressure boilers, the use of supercritical hydrogen as rocket fuel or as a coolant, and the helium

cooling of superconducting magnets.

The critical heat flux⁽¹²⁾ gives the limit of cooling by boiling and shows the upper limit in design. Therefore it has become of major interest from the practical standpoint. However, the critical heat flux is a complex phenomenon in relation to the flow pattern, the instability of flow and so on, and so it is difficult to grasp this phenomenon systematically, where the parametric distortion (Tong) and the inverse mass-velocity effect (Lottes-Petrich-Marchaterre, Bell) occur. Many proposals, such as the local condition hypothesis (Barnett) and the introduction of the concept of boiling length (Bertoletti et al, Hewitt, Herkenrath-Mörkenstein) were made on the critical heat flux, but a generally applicable correlating equation was not obtained until 1980. Recently Katto⁽¹³⁾ investigated the published data in detail and, in the light of theoretical considerations, succeeded in systematically understanding critical heat flux by classifying into four characteristic regimes.

Figure 9 shows the comparison between Katto's correlation and the experimental data for vertical tubes. In this figure the marks (L), (H), (N) and (HP) represent the L-, H-, N- and HP-regimes respectively. The critical heat flux in the L-regime, where the mass velocity is low and the exit quality is high, is of the nature of dryout, while the critical heat flux in the N-regime, where the mass velocity is high and the exit quality is low, is of the nature of depar-

Fig. 8 Approximate correlation of subcooled boiling of water in terms of degree of superheat (McAdams et al, 1949)

Fig. 9 Generalized correlation of critical heat flux for vertical tubes (Katto, 1983)

ture from nucleate boiling. The H-regime is intermediate between the L- and the N-regime, and the HP-regime is the regime which appears in place of the N-regime at a very high density ratio. Here, q_{co} , G , H_{lg} , σ , ρ_l , ρ_v , l and d are the critical heat flux, the mass velocity, the latent heat of evaporation, the surface tension, the density of the liquid, the density of the vapor, the heating length and the inside diameter of the tube, respectively.

Since about 1960, one method (Gambill-Greene) that generates the vortex flow by inserting twisted metal ribbon in the tube, and another method (Swenson-Carver-Szoeke) that adopts a tube with a ribbed internal surface, have been proposed as the counter-measures for improving critical heat flux, mainly for boilers. Furthermore, detailed investigations (Ackerman, Nishikawa-Fujii-Yoshida) are still continuing about internally grooved boiler tubes.

4. Progress in the Research of Boiling Heat Transfer and the Development of Steam and Nuclear Power

Table 2 is a chronological table of steam power (including nuclear power), energy conservation and boiling heat transfer⁽¹⁴⁾. In this table, N. B., F. B., CHF and S. F. are the abbreviations of nucleate boiling, film boiling, critical heat flux and supercritical fluids, respectively. I shall attempt to characterize each of the decades by noting some of the major investigators and their major areas of activity, as well as the main applications of the new knowledge.

The characteristic of boiling research in the 1930's is the clarification of the boiling characteristic curve, and the thorough investigation in the character of nucleate boiling by Jakob, and the establishment of a boiling characteristic curve by Nukiyama can be pointed out. At about the same time the scientific systematization of the thermodynamics concerning heat engines i.e. Engineering Thermodynamics, was accomplished, and the Third International Steam Table Conference, at which the thermodynamic properties of steam were established internationally, was held. The peculiarity in the 1940's was the clarification of the fundamental character of sub-cooled flow boiling by McAdams et al. The 1950's brought about a near explosion of activity in the boiling heat transfer area. The proposal of the correlation of nucleate boiling heat transfer by Rohsenow, Kutateladze and Nishikawa-Yamagata, the introduction of a nucleation factor by Westwater, the development of hydrodynamic theory on burnout by Zuber, the study of film boiling by Bromley, the experiment of flow boiling by Jens-Lottes and so on, can be mentioned. In the 1960's research into practical ap-

plications reached its zenith, with the basic research of the 1950's as a background. The experimental research on the critical heat flux in flow boiling became active, and the research by Macbeth, Tong and Collier, and others, was carried out. The characteristics of 1970's were the augmentation of boiling heat transfer and the establishment of critical heat flux, and the research by Nishikawa, Webb, Tong, Collier and Katto can be pointed out.

Considering the development of steam power corresponding to the progress of thermal science, the invention of the steam engine and the steam turbine at early age was not indebted to thermodynamics and heat transfer as sciences; and the development of technology had preceded the progress of science. The development of the steam boiler also was just the same. The once-through boilers such as the Benson boiler and the Sulzer boiler appropriate for large capacity, were developed before the beginning of research on boiling. In contrast, since 1950 the development of technology has been carried out on the basis of the results of research in the advance of steam power and nuclear power. For example, the water-cooled nuclear reactors i.e. P. W. R. and B. W. R. went into operation in 1957 and in 1959 respectively, and the research of boiling heat transfer which is useful for the removal of the vast heat quantities in a nuclear reactor, had been almost finished about ten years before these reactors went into operation. The terms of Shippingport and Dresden, and those of Mihama and Fukushima in the second column of Table 2, show the beginning years of the operation of the first P. W. R. and B. W. R. in the world, and in Japan respectively. The same thing can be said for the emergence of supercritical power plants. Before the Eddystone power plant and the Anegasaki power plant, which were the first commercial supercritical plants in the world, and in Japan, respectively, went into operation, research into heat transfer to supercritical fluids had been carried out, and the correlation of heat transfer, and the guiding principle for safely avoiding the impairment of heat transfer had already been established.

The oil shock which occurred in 1973 resulted in a new recognition of the limits of oil resources, and serious efforts for the development of new energy and for energy conservation were made. With reference of energy conservation, the development of technology by which augments heat transfer is important. And for the augmentation of boiling heat transfer, the HIGH FLUX tube and the THERMOEXCEL tube were developed. In these cases, the results of research by Gottzmann and Fujie-Nakayama have been put to practical use immediately.

Table 2 Chronological table of steam power, energy conservation and boiling heat transfer
(from A. D. 1930 to A. D. 1985)

A. D.	Heat Transfer	Practice
1930	—	—
—	—Jakob-Fritz (N. B.) 1931	—Sulzer Boiler 1932
—	—Nukiyama (Boiling Characteristic Curve) 1934	
—	—Nusselt (Engineering Thermodynamics) 1934	
—	—3rd International Steam Table Conference 1934	
35	—	—
—	—Schmidt (Engineering Thermodynamics) 1936	
1940	—Insinger-Bliss (Correlation of N. B.) 1940	—
—	N. B. : Nucleate Boiling F. B. : Film Boiling CHF : Critical Heat Flux S. F. : Supercritical Fluids	—Atomic Bomb 1945
45	—	
—	—McAdams (Subcooled Boiling) 1949	
1950	—Bromley (F. B.) 1950	—
—	—Buchberg (Flow Boiling) 1951	
—	—Jens-Lottes (Flow Boiling) 1951	
—	—Rohsenow (Correlation of N. B.) 1952	—Hydrogen Bomb 1952
—	—Kutateladze (Correlation of N. B.) 1952	
55	—Westwater (Mechanism of N. B.) 1955	—
—	—Nishikawa-Yamagata (Correlation of N. B.) 1956	—Calder Hall (GCR) 1956
—	—Dickinson-Welch (S. F.) 1958	—Shippingport (PWR) 1957
—	—Styrikowitsch (Correlation of Heat Transfer to S. F.) 1959	—Eddystone (Supercritical Pressure) 1958
—		—B & W (Ribbed Tube) 1958
—		—Dresden (BWR) 1959
1960	—	—
—	—Goldmann (Boiling-like Phenomena) 1961	
—	—Swenson (Ribbed Tube) 1962	
—	—Macbeth (Correlation of Burnout) 1963	
—	—Shitsman 1963	
—	(Impairment of Heat Transfer to S. F.)	
65	—Nishikawa (Boiling-like Phenomena) 1965	—Tokai (GCR) 1965
—	International Equation of State for Steam 1967	—Anegasaki No. 1 1967
—	(Supercritical Pressure)	
—	—Bergles 1969	
—	(Augmentation of Boiling Heat Transfer)	
1970	—Gottzmann (HIGH FLUX Tube) 1970	—Union Carbide (HIGH FLUX Tube) 1970
—	—Ackerman 1970	—Mihama (PWR) 1970
—	(Ribbed Tube for Supercritical Pressure)	—Fukushima (BWR) 1971
—	—Tong (CHF), Collier (Flow Boiling) 1972	
—	—Yamagata-Nishikawa-Hasegawa 1972	
—	(Correlation of Heat Transfer to S. F.)	
—	—Nishikawa-Ito (Boiling-like Phenomena) 1973	
75	—Nishikawa-Fujii-Yoshida (Cross-Rifled Tube) 1975	—Genkai (PWR) 1975
—	—Fujie-Nakayama (THERMOEXCEL Tube) 1977	—Hitachi (THERMOEXCEL Tube) 1977
—	—Nishikawa-Fujita (Correlation of N. B.) 1977	
—	—Katto (Correlation of CHF) 1978	
1980	—Nishikawa-Ito 1980	
—	(Augmentation of Boiling Heat Transfer)	—CE (Rifled Tube) 1981
—	—Webb (Augmentation of Boiling Heat Transfer) 1983	

Generally speaking, the recent development of technology has been carried out with the progress of science for a background.

5. Conclusion

As a recent trend in boiling research, the augmentation of boiling heat transfer in relation to the efficient use of energy, the burnout in flow boiling in relation to the safety of a nuclear reactor, film boiling in relation to cryogenic engineering, and so on, are the matters of primary concern. The author hopes that the research of boiling progresses increasingly, and that boiling heat transfer develops from an art to a science.

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