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MEMORIES OF MY RESEARCH ON BOILING

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ACCORDING to the request from the Japan Society of Mechanical Engineers, I am writing of my experience under the title "Memories of my research on boiling" with a slight compunction of self-praise.

When water boils at an atmospheric pressure of 1 atm and a temperature of 100°C, the heating surface temperature, t, and the heat rate, Q, show the relationship OACDE, as shown in Fig. 1 which has the maximum C and the minimum D [1].

Since my college graduation, I have been involved in research on boilers for one reason or another. This is probably because I attended lectures by Prof. Shigemitsu Niwa and because I happened to start lecturing on boilers as my first job after graduation.

Since I did not know, however, what specific research should be conducted on boilers, I at first, undertook rather easy measurements of thermal conductivity and so on.

Around the end of the Taisho era or the beginning of the Showa era, there was a Japanese torpedo-destroyer which was blown ashore and wrecked by a windstorm. When I asked an officer why the ship did not escape the storm offshore, I learned that it took 30 min for the boiler to become operative after firing. It usually took more than 5 h for a cylindrical boiler. I wanted to shorten this time and my preliminary research led me to a type of boiler known as a flash boiler which had already gone out of use. If water is sprayed against a red-hot iron plate, as is done in this boiler, steam can be generated instantaneously. But this principle has many big problems in practical use from scale and water impurities contributing to low efficiency.

I then decided on the research objectives of increasing the ratio of vaporization and decreasing the size of the boiler. I undertook the above-mentioned experiment to learn the critical values with such a system.

Old literature had described the t–Q characteristic up to point A in Fig. 1 because it had been assumed that heat transfer would be through a flat plate or metal tube. Q increased with t and no way had been found to supply enough Q to raise t further. I devised a new experimental method where a metal wire was electrically heated in the water. The heat transfer surface area was assumed to be the surface area of the metal wire, and Q and the wire temperature were calculated from the electric current and resistance, respectively. I am sure that modern research in this field still follows the same or similar methods around the world. The difference in temperatures between the surface and the center of the wire is less than 1°C. When raising t, it reaches point C. But since the state between temperatures C and D is unstable, the temperature passes point C instantaneously to point C′, where the wire becomes red hot and burns out in most cases. The local temperature of the wire where bubbles are attached, shown in Fig. 2, must be different from the temperature in other areas. Therefore, there must be a case where the wire burns out at a point on the wire where the temperature exceeds C even though the average temperature of the wire, as calculated from the total electric resistance, is still B. I postulated the existence of point C by observing that the t–Q characteristic curve bending upwards at low temperatures turned downwards around the burn-out point.

Although it was not so difficult to observe the effect of the wire diameter, experiments on flat plates were very hard to perform. Because Q was very large in these experiments, I succeeded in the experiments on flat plates as small as 1 cm^2. I do not know of anyone else who has succeeded in flat plate experiments to observe point B since my experiments.

In the early stages of my study, I found that the temperature of a metal wire easily reached as high as 105°C without the water boiling. I was in the skies because this was contrary, or so I thought, to the invariable principle that "Water boils at 100°C" (a lone exception is super-heated water which is not easily attained). However, when I happened to read an old textbook, *Theory of Heat*, written by Clerk Maxwell, Lord Rayleigh and others, it was lightly described that water boiled when it reached the pertinent boiling

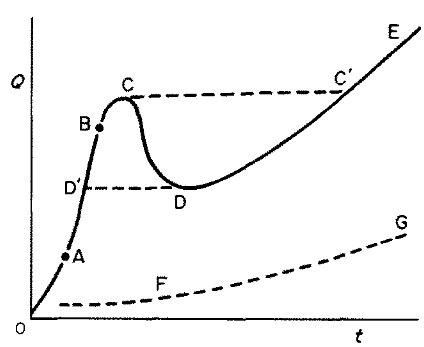

FIG. 1.

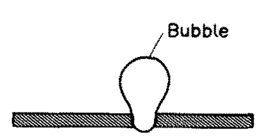

FIG. 2.

temperature for a certain pressure plus the temperature at which the cohesion of the water and its contact surface was overcome, and I realized they had already known the phenomenon.

Since then, I have never written carelessly in the introduction of any paper that such and such has not been known and therefore I have done research on it.

I also tried to experimentally observe the region CD in Fig. 1. When the temperature of the heating surface exceeds point C, the amount of heat generated is greater than the amount of heat transferred to the water, and the temperature of the wire rises rapidly. I wanted to observe this phenomenon, and so purchased an oscilloscope to observe the changes in the current and voltage between the ends of the wire, and to calculate the curve of region CD from them. But this apparatus turned out not to have sufficient accuracy and the experiment was not successful. Thereafter my research assistant Mr Kurose fell ill. Then World War II broke out and I was too busy with one thing or another to continue this research.

After the war two incidents relating to this research of mine took place.

One day I got a phone call from the head office of my university informing me that there had been a phone call from the Ministry of Education to the university with a message from the department of chemistry at G.H.Q. that they had something to ask Dr Nukiyama, a one time professor at the University of Tohoku. They expected me to go to Tokyo. Though it was funny that they called me a former professor, they were wondering how they should reply.

Since the department of chemistry had something to tell me, I went to Tokyo and visited G.H.Q. in front of the Imperial Palace. Several Americans came out to see me, shook hands with me, thanked me for coming, had me sit in a chair and showed me the following letter which had come from California or somewhere. "I am working for such and such university and the research paper by Dr Nukiyama in Japan [with the title of my own paper] had been the most helpful in my research. I have surveyed his papers after that and he seems to have changed his area of research. Considering the importance of his research, however, I am sure that someone else must have continued the research in his place. I hope that you can contact Dr Nukiyama and ask him about the current status of the research in that area in Japan. Furthermore, I want his paper translated into English as I do not understand Japanese. All I know about Dr Nukiyama is that he was a professor at the University of Tohoku before the War."

I replied that I had heard of the research continued in the U.S.A. but I did not think it was currently being done in Japan. I think this reply of mine was almost correct.

At that time, America had absolute power, and I had a slight antipathy toward Americans. When I asked that my travel expenses between Tokyo and Sendai be reimbursed when I left, because I came to Tokyo for the sake of the U.S.A., they agreed it was reasonable and paid for it instantly. I think today that it was rather mean, but it was a demonstration of my resistance.

About that time, an American chemist, Mr Fox and several members of his staff came to Sendai to investigate the research done at our university. He inquired about my research in detail including that described above. He was one of the few persons who understood correctly the difficulties which I had experienced in my research, and asked some searching questions. Finally he asked, "In which area is the result of your research applied to practical use?" "Japanese industries are conservative in the application of new research results." "How come?" "One reason might be that many applications end in failure because the research itself is incomplete for direct application. Another might be that they do not want any wasteful failure." "But graduates rely on the work of their teachers and want to apply it, don't they?" "When the application did not turn out to be successful at once, they would not be free from interference from others. I do not want my graduates to assume such a burden." "I am sorry to hear that. Why don't you come to the U.S.A. to carry on your research?"

I could not answer easily because I understood that what the American said was exactly what he thought. After a while, "Nowadays it's hard for a Japanese to get bread. I have led my long life for the sake of Japan. I can not take it into my head to work comfortably in the U.S.A. I would like to contribute to the development of Japanese industries and then think about it when the Japanese have achieved a more comfortable life." "That idea is very good."

Since about that time, I have extended my research area to include heat management in plants, tests and evaluations of boilers and so on to contribute to fuel savings. I am afraid, however, that this is far from the research intended by the title of this essay.

Immediately after the termination of the war, I did not have funds for research but I wanted to continue the research described above. Therefore, I undertook experiments, where red-hot iron was put into water of constant temperature. The change in the temperature at the center of the sample was measured and changes in temperatures over time at the surface of and at various points in the sample were calculated from it. The amount of heat transfer was also calculated from the temperature gradient to trace the DCBA line from point D in Fig. 1. In this case, however, it was not my major purpose to obtain the exact DCBA line but to measure the height of point B for use in research on quenching liquids. Since I assumed that the line downwards curved around point B because the amount of vapor with poor heat conductivity increased and covered the heating surface, I used a sodium bicarbonate aqueous solution. Contrary to my expectations point B got higher. I then assumed that salt or muddy water would have the effect of lowering point B because a solid would be left on the surface after evaporation, but the result was that point B rose higher. This is probably because the intense boiling prevents salt or mud from forming a membrane on the heating surface.

When I happened to have some sulfite pulp liquor on hand, and diluted it with water, point B lowered with the concentration of the liquor. I interpret this as the result of an organic compound like this being charred onto the metal surface, which impairs the contact of the water with the metal surface, lowering point B. This must be the reason why oil quenching makes for milder quenching than water.

This means that a substance like sulfite pulp liquor, which can be diluted with water and is likely to be charred makes it possible to get a point B of any height. In other words, this makes quenching controllable to any degree desired. In this sense, this type of liquid is superior to oil. However, oil quenching gives the quenched material an almost constant hardness since point B is hardly affected by the oil temperature, and oil prevents rust from forming if the materials are left as they are after quenching. This is why oil quenching cannot be abandoned.

In Showa 22 (1947), Dr Tanazawa and his co-workers published an article asserting the existence of the maximum of cooling, like point B, through their experimental research, where iron plate was quenched by spraying water on it [2].

In March 1947, at the Tokai regional meeting of this society, Dr Takeyama presented the results of his research where he obtained the line in Fig. 1 through the experiments with a metal wire and a water spray, the water–air ratio was varied and the line lay in between the solid line for water and the broken line FG for air in Fig. 1. On the other hand, Dr Yamagata and Dr Nishikawa are studying boiling form, that is to say the shape of bubble, and are conducting other analyses of heat transfer.

In Showa 34 (1959), Dr Tanazawa made a presentation in London showing that in his research on IC engines he found that the relationship between the vaporization rate and the wall temperature when an oil drop hits against a hot wall was the same as shown in Fig. 1 [3]. I was deeply moved when I listened to the recording of his speech and the audience applauded when he said, "If you would agree, I would like to name point B the Nukiyama point." which corresponds to point D, called the Leidenfrost point.

When I happened to undertake the experimental research on boilers, it was ahead of that in Europe and the U.S.A. Recently this research is attracting attention because the vaporization ratio in the boilers for nuclear energy is very high. Also, research has become more active in Europe and the U.S.A. than in Japan.

However, nowadays, much good research is being done in Japan. I am very happy to see my research fading as a result of recent excellent work.

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