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Discussion

R. F. Larson.[7] It should be borne in mind, and perhaps emphasized, that these tests are primarily tests in heating liquid, water, making use of the intermediate processes of boiling and subsequent condensation. Obviously, the heat-transfer rate q/A will be a function of the extent to which this entire process is completed, either within the test section or beyond it. With this in mind it is clear that the results are also functions of the geometry of the apparatus, the diameter and length of the tube, as well as its position. Obviously, an inclined or horizontal tube would not give the same results as a vertical one, thus the rates obtained should not be taken as representative of rates obtainable from other possible arrangements.

The entire process is complex and cannot be simplified readily to considerations of film coefficients alone, unless the complete process is completed at the heat-transfer surface or adjacent to it. The authors, perhaps wisely, did not calculate and correlate such film coefficients for the case of intermediate boiling. Failure to recognize this may account for lack of correlation of coefficients possible between the results of various investigators. The unstable conditions are undoubtedly dynamic phenomena set up by vapor-locking of the tubes at the top and a passage over to the film-boiling range, with resultant overheating and failure. The entire process is then not completed within the tube, and the safe capacity of the tube has been surpassed.

That a smaller temperature excess, $T_w - T_b$, above the normal boiling temperature follows upon polishing and perhaps otherwise cleaning the tube surface is indicated from both physical and surface-energy considerations. The condition for bubble initiation on the wall surface depends upon the wettability or the adhesion tension ($\sigma_{SV} - \sigma_{LS}$), or better yet, the combination $\sigma_{LV} + (\sigma_{SV} - \sigma_{LS})$, which establishes the liquid superheat necessary.[8] This property is not homogeneous along a metal surface, but varies according to homogeneity of crystalline structure, presence of impurities, and cleanliness.

A high adhesion tension means a high degree of wettability and this will determine the size and shape of bubbles formed on the surface, and how soon they will be released and swept away to be later condensed, if such occurs. The ebullition process is intermittent with large fluctuations of liquid superheat at a point, the result being a very efficient type of turbulence created just where it will do the most good, at the very surface film. A relatively strongly wetted surface such as stainless steel promotes this process, the nuclei being sufficient in number, yet not too many, and small enough to prevent film boiling from being established even at fairly high rates of heat transfer. Geometric consideration of surface roughness will explain why surface bubbles adhere longer on rough surfaces, and, hence, inhibit the desirable fluctuations and resulting surface turbulence. Surface deposits not only add resistance to heat transfer but may change the surface wettability considerably.

More experimentation of this type using other heating surfaces and other liquids, thus giving a wide range of wettability or surface free energy, are in order. That a lower pressure drop accompanies the surface-boiling phenomenon, in spite of the added turbulence, is probably due to the presence of the vapor phase; and offers added motive for investigating further the use of boiling to improve over-all heat transfer. However, how far one can go in this direction without encountering vapor lock or vapor film boiling depends upon not only control of surface ebullition but also upon control and disposal of the vapor bubbles after they leave the surface. The entire process, both boiling and condensation, if such is to occur, should be considered in the design of such a heat exchanger. If boiling and evaporation are the aim, then disposal of vapor is of prime importance.

Authors' Closure

The authors appreciate Professor Larson's comments on this paper. They agree that more experimental work of this type with other heating surfaces and other liquids is in order. Since the publication of this paper, an experimental program with aniline and *n*-butyl alcohol has been completed, and the results of this study will be published soon.

As Professor Larson points out, the heat-transfer process with surface boiling is complex and does not lend itself readily to a theoretical treatment. However, the results from recent tests at this laboratory with an annular test section (with forced flow) and with a stainless-steel strip submersed in a subcooled water bath[9] have provided additional clues to the mechanism of surface boiling and its limitations. Data were obtained regarding the upper limit of heat flux which can be removed by water with surface boiling, and also the factors causing the breakdown of the heat-transfer processes were studied qualitatively. The annular test section which was used for these tests was formed between a stainless-steel heating tube ($^3/_8$ in. OD) and a transparent pyrex jacket ($^5/_8$ in. ID). The heated section of the tube was 7 in. long. The test section was located in a vertical position, and the cooling water from the laboratory supply system entered at the bottom.

Burnout conditions were investigated at heat-flux values from 2 to 8 Btu/sq in. sec, in the velocity range from 2 to 14 fps, and the pressure range from 15 to 75 psia. The results of the tests are correlated in a manner suggested by McAdams in Fig. 17 of this closure, where the heat flux at burnout is plotted against the product of the entrance velocity times the subcooling tem-

[7] Professor of Mechanical Engineering, University of Illinois, Urbana, Ill. Mem. ASME.

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[9] "Photographic Study of Bubble Formation in Heat Transfer to Subcooled Water," by F. C. Gunther and F. Kreith, Heat Transfer and Fluid Mechanics Institute, ASME Publication, May, 1949, pp. 113–138.

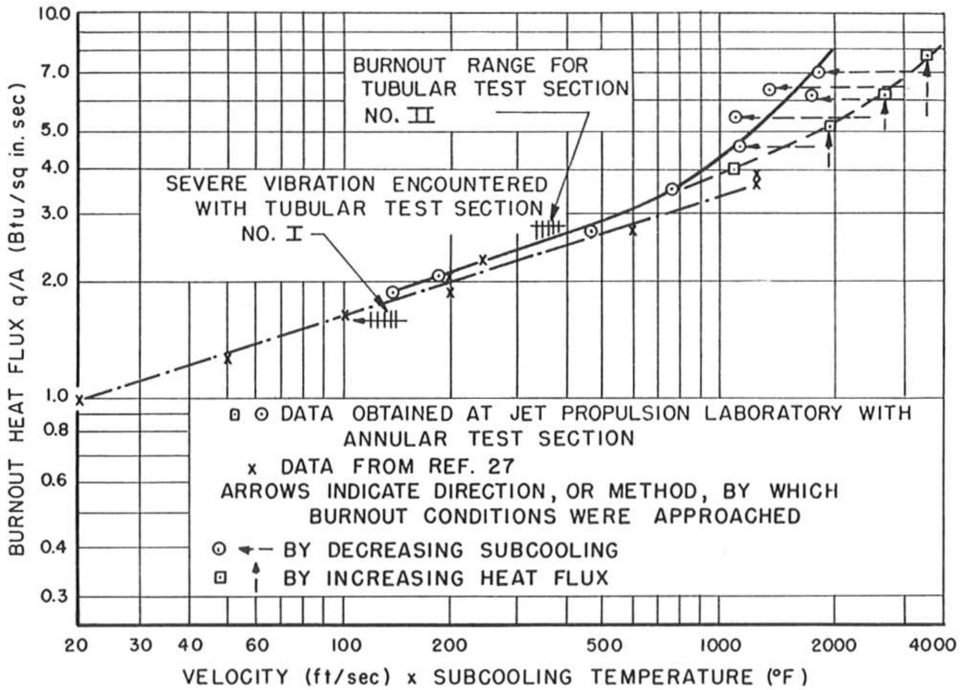

Fig. 17 Burnout Conditions for Annular Test Section
(Data for tap water.)

perature (which is defined as the temperature difference between saturation temperature at the test pressure and the bulk temperature of the liquid). The results obtained by McAdams, et al,[10] in burnout tests with water are superimposed on the graph of Figure 17. McAdams used an annular test section which was 3.75 in. long and was formed between a stainless-steel tube 0.25 in. OD and a jacket 0.77 in. ID. The following data are also shown in Fig. 17:

1 Burnout range which had been encountered with the tubular test section No. II.

2 Range of unsteady flow conditions (vibrations) with the tubular test section No. I.

It can be seen from an inspection of Fig. 17, that the results obtained with test sections of widely varying geometry are in agreement.

In passing, it is of interest to point out that the burnout heat flux appears to depend upon the suddenness with which the critical conditions are approached. Two methods of approaching burnout conditions were utilized during the tests for which the data are shown in Fig. 17:

1 In some tests, burnout conditions were approached at a constant heat flux (after steady-state cooling conditions had been established) by decreasing the amount of subcooling by reducing the pressure on the test section and/or by decreasing the velocity of the coolant liquid. (Solid curve.)

2 In an alternate approach to burnout conditions, the heat flux was increased in steps of about 0.1 Btu/sq in. sec, and the flow and pressure were maintained constant. However, for each heat-flux level, which was determined by the voltage across the heater tube, it was necessary to apply the electric power instantaneously to the test section. (Dashed curve.)

[10] "Heat Transfer at High Rates to Water With Surface Boiling," by W. H. McAdams, J. N. Addoms, and W. E. Kennel, Department of Chemical Engineering, Massachusetts Institute of Technology, December, 1948. (Report issued by Argonne National Laboratories.)

When technique (2) was used, burnouts occurred at higher velocities and at lower bulk temperatures (more subcooling) than when burnout conditions were approached by method (1). The directions or methods by which burnout conditions were approached are indicated in Fig. 17 by arrows. It is believed that when burnout conditions were approached by method (2), the rate of heating was so rapid that the critical range of surface temperature was traversed in a time which was comparable to or less than that required to establish equilibrium surface boiling conditions, and that the temperature of the tube could have exceeded momentarily the equilibrium temperature, resulting in a premature burnout. Based upon the photographic observations reported[9] previously, the time required to establish the surface-boiling heat-transfer mechanism is estimated to be from 0.001 to 0.005 sec, while the time available in approach (2) is estimated to be of the order of 0.002 sec at a heat-transfer rate of 4 Btu/sq in. sec, and becomes even less at larger values of heat flux.

A clue to the reason why the geometry of the test section is of relatively small importance upon the burnout limits was obtained from visual inspection and photographs of the boiling mechanism in the annular test section. It was observed that when the bulk temperature of the water in the test section was subcooled 75 deg F or more, only a very small amount of vapor existed in the main stream. Furthermore, the burnouts in the annular test section were not caused by a vapor lock at the top of the annulus, but rather by local vapor blanketing. It appears that this blanketing phenomenon is insensitive to the over-all geometry of the test section.

Additional information regarding the mechanism of surface boiling has been obtained from high-speed motion pictures of the bubble growth and collapse cycles on a flat strip heater.[9] The conclusions drawn from these data are substantially in agreement with the foregoing argument, namely, that the heat transfer process in the surface-boiling regime is dependent only on local conditions adjacent to the surface, and is relatively independent of the over-all geometry of the system.