ROUGHENING OF HEAT TRANSFER SURFACES AS A
METHOD OF INCREASING HEAT FLUX AT BURNOUT

MASTER

By

W. S. Durant and S. Mirshak
Savannah River Laboratory
E. I. du Pont de Nemours & Co., Inc.

INTRODUCTION

In water-cooled nuclear reactors, the reactor power is frequently limited by the maximum or burnout heat flux of the fuel assemblies in the reactor. It is therefore advantageous from a safety and economic standpoint to increase the ability of a surface to dissipate heat without increasing the power required to pump coolant through the reactor. Roughening the surface of a fuel element is one method of increasing the heat flux at burnout without the requirement of increasing pumping power.

This report presents the results of experiments to determine the heat flux at burnout for rough surfaces. A correlating equation for the effect of friction factor on the burnout heat flux is presented for the data.

SUMMARY

The burnout heat flux and friction factors for rough surfaces were measured for vertical tubes cooled by downward flow of water. An increase in the burnout heat flux of as much as 100% over a smooth surface was obtained at the same coolant velocity, temperature, and pressure. A net gain of as much as 80% in heat flux at burnout is possible if the coolant channel is widened to permit the same flow at the same pumping requirements as a smooth surface.

The results of 50 experiments were correlated empirically by the following equation:

$$(Q/A)_{BO} = 266,000 (1+0.0365V)(1+0.00914T_S)(1+0.0131P)(0.3+0.7R_f) \quad (1)$$

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where $(Q/A)_{BO}$ = heat flux at burnout, $P_{cu}/hr-ft^2$

V = coolant velocity, ft/sec

T_S = subcooling, $^{\circ}C$

P = pressure, psia

R_f = friction factor of rough surface divided by the friction factor of a smooth surface at the same Reynolds Number.

The correlation fits the data with a maximum deviation of 24%.

The range of variables covered in the experimental work and by the correlation is as follows:

1. Velocity - 10 to 32 ft/sec
2. Subcooling - 20 to $82^{\circ}C$
3. Pressure - 33 to 70 psia
4. Equivalent diameter of coolant passage - 0.25 to 0.75 inch
5. Geometry of heated surface - 0.5 inch OD tube
6. Type of roughness - threads, diamond knurls, and sandblasted
7. Flow of water - downward
8. Heated surface material - Type 304 stainless steel, Zircaloy-2
9. Heat flux - 1,000,000 to 2,000,000 $P_{cu}/hr-ft^2$
10. Relative friction factor - 1.00 to 2.90

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The burnout heat flux was measured with electrically heated tubes cooled with downward flowing water in annuli formed by the outer surfaces of the heaters and the inner surfaces of the glass housing.

DISCUSSION

Background

The ability of a surface to dissipate heat is known to be influenced strongly by surface roughness or other turbulence promoters.

Many experimenters⁽¹⁾ have determined the forced convection heat

transfer coefficients for turbulence promoters in heat exchangers, pipes and rectangular channels. Although a substantial gain in heat transfer coefficient was realized, a large increase in friction factor, or pumping power required to move the fluid past the surface, was generally believed to overshadow any gain in heat transfer. In pool boiling, where pumping requirements are of no consequence, the heat transfer coefficient was reported to be higher for rough surfaces than for smooth surfaces^(2,3). Averin⁽²⁾, however, found that as pool boiling progressed to near burnout conditions, the increase "ceased to be apparent", as was also the case at burnout. Data presented in this report, though, showed that rough surfaces cooled by forced flow of water had heat fluxes at burnout up to twice that of a smooth surface at the same velocity, pressure, and subcooling.

Description of Equipment

A detailed description of the flow loop used for the burnout tests is presented in DP-355⁽⁵⁾. Distilled water flow in a closed loop from the pump through an orifice meter, downward through the test section, a heat exchanger, a head tank, and back to the pump. The quality of the water in the stainless steel loop was maintained by a mixed bed ion exchange resin.

The following basic types of surface roughness were evaluated in this study:

- 1) longitudinally knurled (grooved) surfaces
- 2) diamond knurled surfaces
- 3) circumferentially grooved (threaded) surfaces
- 4) sandblasted surfaces

The test specimens were Type 304 stainless steel tubes. The tubes were seamless and had an outside diameter of 1/2 inch with a wall thickness of 0.120 inch. The outer surface of the tubes was roughened to a controlled depth by cold working or machining on a lathe. Circumferential grooves were made in the tubes by cutting 30 and 64 threads per inch. The included angle at the base of the grooves was 60°. The knurled surfaces were formed on the tubes with knurling tools of the appropriate shape to form the longitudinal knurls and either fine or medium diamond knurls.

The depth and dimensions of the surface roughness were obtained from profilometer tracings and photographs. Figures 1 and 2 are typical profilometer tracings and photographs of the surfaces of the rough tubes.

The test section consisted primarily of the tubular heater, glass housing tube, copper buses, flow guides and the casing.

Pyrex brand glass was used to construct the heavy wall, precision bore housings. The length of the housings were 30-1/2" long, and the inside diameters ranged from 0.750 to 1.250". The heaters were centered in the housings to form an annulus between the outer wall of the heater and the inner wall of the housing.

Copper buses, clad with stainless steel, were silver soldered into the ends of the heater. The bus diameter was the same as the heater diameter for nine inches beyond each end of the heater and tapered to a diameter of one inch. Flow guides with 7-1/2° tapers directed the flow into and from the annulus to inhibit end effects.

Thermal expansion of the heater was through a flange at the bottom of the test section. Lead weights were suspended from the lower bus to overcome the friction of the O-rings used in the flange.

Concentricity of the heater and the housing was determined with a cathetometer. It was possible to observe the entire heater through "Plexiglas" windows in the casing.

Direct current was supplied to the test section by eight welding generators, connected in parallel with a total rating of 7200 amperes at 40 volts; thus approximately 300 kw of power were available for resistance heating of the tubes.

Coolant temperatures were measured at the entrance and exit to the test section with copper-constantan thermocouples. Operating pressures were measured at the top and bottom of the annulus, and the flow was metered through an orifice plate.

Experimental Procedure

The surfaces of the tubes were degreased with acetone or trichloroethylene before the tubes were mounted in the test section. The system was filled with distilled water and deaerated for 20 minutes at a temperature of 80°C while the heated surface was operated at a low heat flux. A deionizer maintained the resistivity of the water at approximately four megohm-cm. After deaeration, the coolant velocity, pressure and heat flux were set at predetermined values. By throttling the cooling water to the heat exchanger, the temperature rise of the coolant was controlled at approximately 1°C per minute until burnout occurred.

The criterion for burnout was the appearance of a self-propagating, incandescent spot at the lower end of the test section. Any mechanical malfunctions which resulted in premature burnouts were easily observed through the transparent casing windows and housing tubes.

Results

The experimental results for 50 burnout tests are presented in Table I. The results are related to the point conditions at the burnout site. All the burnouts occurred near the lower end of the test specimens, as would be expected with uniform heating of the surfaces. Figure 3 relates the effect of friction factor on the burnout heat flux.

Discussion of Results

The burnout heat flux for rough surfaces is substantially higher than for smooth surfaces at the same coolant velocity, temperature and pressure. This increase in burnout heat flux is also accompanied by a substantial increase in the friction factor, which appears to be the controlling variable. Figure 3 shows the effect of friction factor on the burnout heat flux for the 50 experimental data points. The increase in burnout heat flux over a smooth surface is linear with increasing friction factor and may be expressed by the function

$$\frac{(Q/A)_{\text{Rough}}}{(Q/A)_{\text{Smooth}}} = (0.3 + 0.7R_f) \quad (2)$$

where R_f is the friction factor of the rough surface divided by the friction factor of a smooth surface compared at the same Reynolds Number. The measured burnout heat fluxes of the rough surfaces are compared to the burnout heat fluxes for smooth surfaces as determined by the correlation in DP-355. Thus the burnout heat flux of a rough surface may be expressed by the correlation:

$$(Q/A)_{BO} = 266,000 (1+0.0365V)(1+0.0131P)(1+0.00914T_s)(0.3+0.7R_f) \quad (1)$$

where

$(Q/A)_{BO}$ = heat flux at burnout, Pcu/hr-ft²

V = coolant velocity, ft/sec

T_s = subcooling, °C

P = pressure, psia

R_f = friction factor of the rough surface divided by the friction factor of a smooth surface at the same Reynolds Number.

The type of surface roughness does not appear to significantly affect the burnout heat flux at any given friction factor. The diamond knurl, however, can be machined with a consistently rougher surface than the thread and shows more predictable characteristics of burnout heat flux from the measured friction factor than the thread.

In tests with longitudinally grooved tubes severe vibration of the test section occurred during local boiling, and the tests had to be terminated prior to burnout. Vibration is known to improve the heat transfer coefficient, and occurred only in runs with the longitudinal groove. It is believed that the vibration was the primary cause of the improved heat transfer, rather than the roughness. Visual observations of the test specimens during the runs indicated that the vapor being formed on the heated surface was rising in the grooves on the tube surface. The vapor columns appeared to oscillate as they progressed up the annulus. It is hypothesized that the upward flowing vapor was condensed by the downward flowing water and the resulting pulses set up the vibration as the condensed vapor reversed direction and flowed downward.

The burnout heat flux of rough surfaced Zircaloy-2, as well as that of stainless steel, may be predicted by Equation (1). This would be expected as the burnout heat flux of smooth-surfaced Zircaloy-2 was in agreement with tests conducted with smooth-surfaced stainless steel.⁽⁷⁾

The two tests reported here were 10% below the correlating equation, but well within the scatter of the data.

The surface area for heat transfer does not appear to be a controlling variable of the burnout heat flux. The maximum surface area for the diamond knurl is 1.41 times that of a smooth surface and for the 60° thread is 2.0 times that of a smooth surface; yet the thread shows no better characteristics than the diamond knurl.

Plotted in Figure 4 are the friction factors of the various rough surfaces tested for several values of the parameter, equivalent diameter divided by depth of the roughness. Also plotted for comparison are the published values of friction factors versus the roughness ratio for flow inside pipes. As shown in the Figure, the friction factor of the rough surfaces increases with decreasing channel thickness or increasing roughness depth. The effect of the equivalent diameter and depth of roughness on the burnout heat flux is incorporated in the correlation, Equation 1, via the friction factor. A negligible effect of equivalent diameter on burnout of smooth surfaces was reported in DP-355; however the friction factor did not vary with equivalent diameter at a given Reynolds number in this case.

The application of rough surfaces to water-cooled, heterogeneous reactors, can afford a wider margin of safety in operation or an increased power output. In the case of fuel assemblies where the quantity of coolant and available head are fixed by other considerations, the benefits of rough surfaces may be realized even though the friction factor would increase in annuli of the same dimensions as those used with smooth surfaces. For example, in thin annuli, where the velocity is approximately inversely proportional to the equivalent diameter, it follows from the Fanning friction equation that the velocity for a rough surface is inversely proportional to the cube root of the friction factors for a constant head loss across the annulus. Therefore to maintain a flow and head loss equivalent to the smooth surfaced assembly,

the coolant annuli must be enlarged by an amount equalling $\sqrt[3]{\frac{f_r}{f_s}}$. This may be accomplished by altering the housing and/or the fuel dimensions. The gain in burnout heat flux of a rough surface over a smooth surface is given by Equation (3) for conditions of constant flow and head loss in thin annuli:

$$\left[\frac{(Q/A)_{BO\ r}}{(Q/A)_{BO\ s}} \right]_{\Delta P, F} = \left[\frac{1 + 0.0365V_s \sqrt[3]{1/R_f}}{1 + 0.0365V_s} \right] \left[\frac{(Q/A)_{BO\ r}}{(Q/A)_{BO\ s}} \right]_V \quad (3)$$

where s refers to a smooth surface and r refers to a rough surface. The subscripts P and F refer to operation at constant head loss and flow, while the subscript V refers to constant velocity. In terms of friction factors Equation (3) reduces to:

$$\left[\frac{(Q/A)_{BO\ r}}{(Q/A)_{BO\ s}} \right]_{\Delta P, F} = \left[\frac{1 + 0.0365V_s \sqrt[3]{1/R_f}}{1 + 0.0365V_s} \right] \left[0.3 + 0.7R_f \right]_V \quad (4)$$

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TABLE I
BURNOUT HEAT FLUX OF ROUGH SURFACES

Run No.	Type of Roughness	Depth of Roughness, In.	Velocity, Ft/Sec.	Pressure, psia	Sub-cooling, °C	Channel Thickness, In.	Burnout Heat Flux Pcu/hr-ft ²	Burnout Heat Flux Relative to Smooth Surface	Friction Factor Relative to Smooth Surface	Reynolds Number	Equivalent Diameter Depth of Roughness
1	Threaded, 30/in.	0.009	28.7	48.7	37.6	0.187	1,790,000	1.49	1.84	260,000	41.7
2	304 stainless steel	0.013	16.8	33.8	51.6	"	1,408,000	1.54	1.65	99,000	28.8
3	"	0.009	17.0	52.1	50.3	"	1,675,000	1.58	2.01	116,000	41.7
4	"	0.009	11.1	48.2	43.9	"	1,294,000	1.52	2.01	75,000	41.7
5	"	0.008	16.7	62.2	44.4	"	1,600,000	1.30	1.44	109,000	46.9
6	"	0.009	24.9	63.2	58.0	"	1,970,000	1.39	1.61	160,000	41.7
7	"	0.009	25.1	44.3	56.7	"	1,750,000	1.44	1.57	160,000	41.7
8	"	0.012	24.8	43.7	28.6	"	1,442,000	1.43	1.74	226,000	31.2
9	"	0.012	18.3	49.7	35.9	"	1,310,000	1.36	1.68	155,000	31.2
10	"	0.008	19.0	63.2	61.7	"	1,580,000	1.22	1.49	125,000	46.9
11	"	0.008	18.8	43.7	25.7	"	1,130,000	1.18	1.45	127,000	46.9
12	"	0.016	19.0	65.2	54.9	"	1,520,000	1.21	1.62	144,000	23.4
13	"	0.014	29.7	43.8	41.0	"	1,820,000	1.51	1.94	237,000	26.8
14	"	0.009	25.8	43.6	37.2	0.250	1,505,000	1.39	1.37	298,000	55.5
15	"	0.009	15.0	45.7	37.4	"	1,020,000	1.16	1.37	172,000	55.5
16	"	0.009	20.1	48.4	28.1	"	1,280,000	1.35	1.39	264,000	55.5
17	"	0.003	19.3	64.7	82.1	"	1,810,000	1.22	1.07	147,000	166.7
18	"	0.003	31.5	53.7	36.3	"	1,430,000	1.11	1.22	312,000	166.7
19	"	0.003	30.0	45.1	39.8	"	1,630,000	1.35	1.28	344,000	166.7
20	"	0.003	30.3	47.9	51.1	"	1,570,000	1.18	1.10	317,000	166.7
21	"	0.004	30.3	43.7	52.4	"	1,610,000	1.24	1.29	293,000	125.0
22	"	0.004	15.0	69.6	58.2	"	1,550,000	1.28	1.05	152,000	125.0
23	"	0.003	9.9	80.0	76.1	"	1,470,000	1.17	1.08	78,000	166.7
24	"	0.006	20.2	49.5	57.1	0.187	1,951,000	1.68	1.52	129,000	62.5
25	"	0.006	20.2	50.2	52.3	"	1,800,000	1.59	1.55	137,000	62.5
26	"	0.018	21.0	53.7	60.0	0.375	1,685,000	1.36	1.60	304,000	41.7
27	"	0.018	17.6	50.4	36.2	0.125	1,887,000	1.96	2.08	80,000	13.9
28	Threaded, 64/in.	0.009	20.0	49.2	48.0	0.187	1,929,000	1.77	1.64	141,000	41.7
29	Diamond Knurl, 630 Points/sq. in.	0.013	15.2	49.7	19.7	0.125	1,718,000	2.13	2.46	93,000	19.2
30	304 stainless steel	0.005	22.5	49.7	62.5	0.250	1,790,000	1.43	1.71	186,000	100.0
31	"	0.005	27.5	46.2	53.7	0.187	1,810,000	1.42	1.80	188,000	75.0
32	"	0.008	20.0	49.7	70.3	"	1,960,000	1.57	2.04	108,000	46.9
33	"	0.008	20.3	49.9	48.6	"	1,760,000	1.59	2.15	143,000	46.9
34	"	0.012	20.0	49.2	53.5	"	1,900,000	1.68	2.24	128,000	31.2
35	"	0.015	17.0	49.7	27.3	0.125	1,880,000	2.12	2.90	83,000	16.7
36	Diamond Knurl, 235 Points/sq. in.	0.008	10.0	49.7	53.2	0.187	1,230,000	1.38	1.53	60,000	46.9
37	304 stainless steel	0.008	9.9	49.7	52.2	"	1,293,000	1.46	1.53	61,000	46.9
38	"	0.008	20.1	49.7	61.9	"	1,900,000	1.59	1.76	119,000	46.9
39	"	0.008	14.9	49.7	61.4	"	1,610,000	1.52	1.64	84,000	46.9
40	"	0.008	20.0	49.7	59.5	"	1,773,000	1.51	1.78	124,000	46.9
41	"	0.015	18.2	49.9	42.9	"	1,840,000	1.71	2.21	120,000	25.0
42	"	0.015	18.1	50.0	40.1	0.125	1,810,000	1.81	2.52	77,000	16.7
43	"	0.015	16.6	48.5	43.2	0.187	1,580,000	1.52	1.80	108,000	25.0
44	"	0.015	16.9	32.7	34.9	"	1,301,000	1.60	1.80	124,000	25.0
45	"	0.019	20.6	46.9	32.1	0.250	1,510,000	1.55	1.57	264,000	26.3
46	"	0.019	15.0	59.4	43.6	"	1,551,000	1.51	1.70	172,000	26.3
47	"	0.019	25.3	43.0	27.4	"	1,530,000	1.56	1.66	324,000	26.3
48	Sandblasted, 304 stainless steel	0.001	19.7	49.7	53.3	0.187	1,550,000	1.38	1.63	134,000	375.0
49	Diamond Knurl, 235 Points/sq. in.	0.015	14.9	50.7	63.8	0.187	1,500,000	1.39	1.78	84,000	25.0
50	Zircaloy-2	0.015	15.0	49.6	41.0	0.187	1,300,000	1.41	1.80	119,000	25.0

FIGURE 1

SURFACE CHARACTERISTICS OF A TUBE
WITH A MEDIUM DIAMOND KNURL, 0.008" DEEP

a. Photograph of Tube
(Mag. 1.3 X)

c. Profilometer Tracing

FIGURE 2

SURFACE CHARACTERISTICS OF A TUBE
WITH 30 THREADS PER INCH, 0.006" DEEP

a. Photograph of Tube
(Mag. 1 X)

b. Longitudinal Section (Mag. 4.3 X)

FIGURE 3

FIGURE 4

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