theoretical result, the scatter of the data being less than ±10 percent in a wide range of variables.

The data collected in WAPD-188 at 1000 and 2000 psia were correlated within ±20 percent. Considering the disagreement between the different sets of data in this report, we conclude that the usefulness of the method has been demonstrated.

Comparisons with the CISE data at 70 kg/cm² revealed that about 70 percent of the data were correlated within ±10 percent. The remaining 30 percent of the data showed burnout values up to several hundred percent too low. We suggest that hydrodynamic loop instabilities may have caused the low burnout values, and excluding these points from the present discussion, we conclude that also in the case of the CISE data satisfactory agreement exists between experimental results and the correlation.

Finally we conclude that the accuracy of the correlation can be improved appreciably in the high pressure region when additional and more reliable burnout data have been obtained.

Acknowledgments

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DISCUSSION

Hans K. Fauske[2]

In this paper a physical model based on the work of Isbin, et al., has been utilized to correlate the data. The authors' main object in this paper is to show that the burnout is strictly a local phenomenon independent of subcooling or inlet conditions and length-to-diameter ratio.

It is first shown that burnout is independent of N_{sc} and L/D ratio from experimental data. Numerous arguments that burnout is dependent or independent on these parameters can be found in the literature and will not be discussed here. The authors then proceed by showing that the theoretical results of Isbin, et al., can be simplified to and reduced to a set of equations, mathematically saying the same as equation (4), namely

$$f(p,\ q/A,\ \dot{m}/F,\ X_{BO}) = 0.$$

The question raised here is if the authors have really proved the noneffect of N_{sc} and L/D ratio by utilizing the proposed model by Isbin, et al. The appearance of L/D ratio and N_{sc} in equations (5), (6), and (7) comes about merely from a substitution of a simple heat balance of the following form:

$$q/A = \frac{\dot{m}/F\ h_{fg}(X_{BO} + N_{sc})}{4L/D}.$$

By eliminating L/D ratio from equations (5) and (6) and setting N_{sc} equal to zero, the authors now obtain a set of equations which say that the burnout is strictly a local phenomenon. Then it is pointed out that the obtained solutions must be checked in order to avoid a violation of the heat balance discussed above. But this heat balance has been violated in equation (7) by setting $N_{sc} = 0$ in evaluating the constants ϵ and b. It appears, therefore, somewhat dangerous to conclude that burnout is a local phenomenon only by applying the above procedure. The net result rather is a new set of parameters ϵ, b, etc., to the expense of setting $N_{sc} = 0$ and, hence, violating the heat balance, when the latter is combined with the differential equations obtained from the physical model.

T. M. Grace[3] and H. S. Isbin[4]

We are appreciative of Dr. Becker and Mr. Persson's use of the Vanderwater model in their detailed and extended studies. Furthermore, we are well aware of the criticisms usually voiced regarding such factors as L/D ratios, inlet subcoolings, and burnout as a local phenomenon or one determined by the "history" of the flow. For the present discussion, the best approach is to examine the results of the Becker-Persson data and analyses in their Figs. 5, 6, and 7. The agreement between experimental and predicted burnout conditions is, indeed, very encouraging. If we accept Figs. 9 and 10 as being typical of the Becker data, then it is apparent, for the burnout flow tests reported, that the inlet subcooling and L/D ratio have little or no effect on the predictions. How far one might go in applying the model to other sets of burnout data (CISE, Harwell, ANL, MIT, Westinghouse, and others) are questions still open for discussion.

Dr. Becker has been helpful in supplying his burnout data to us, and we, in turn, are working on a modification of the Vanderwater model which does successfully predict the Becker burnout data.

The data on two-phase heat transfer indicate that there are three regions of heat transfer: (*a*) nucleate boiling, (*b*) convective-dominated heat transfer, and (*c*) a liquid-deficient region. In both regions (*a*) and (*b*), heat transport is highly efficient, whereas in region (*c*), it is not. Thus burnout, as limited to tests with steady-state flows, can occur either by tranistion from region (*a*) to region (*c*), or from region (*b*) to region (*c*). The two distinct types of burnout are called DNB, departure from nucleate boiling (transition from (*a*) to (*c*)), and TCR, transition from the convec-

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Table 1 Correlation of burnout data obtained by Becker

Comparison of heat fluxes predicted by the film flow model with experimentally measured heat fluxes

Length = 3120 mm. Diameter = 3.94 mm.

ΔT_{sc} °F	$G/10^6$ lb/hrft^2	P psia	$q_{exp.}/10^6$ BTU/hrft^2	$q_{calc.}/10^6$ BTU/hrft^2	deviation percent
333.9	.601	520.6	.202	.191	- 5.5
327.2	.612	489.3	.203	.192	- 5.5
321.8	.612	467.9	.203	.190	- 6.7
303.8	.622	389.7	.205	.186	- 9.2
303.8	.628	389.7	.205	.188	- 8.5
295.2	.635	357.0	.206	.187	- 9.4
287.1	.661	325.7	.205	.190	- 7.2
271.3	.677	294.4	.206	.190	- 7.8
264.8	.705	268.8	.206	.194	- 6.2
251.8	.727	243.2	.207	.195	- 6.0
238.3	.756	210.5	.208	.196	- 5.5
228.1	.797	189.2	.208	.201	- 3.3
222.3	.805	182.1	.208	.201	- 3.1
208.8	.872	156.5	.208	.210	.8
196.2	.937	133.7	.208	.217	4.2
183.2	.973	115.2	.209	.219	5.1
333.5	.608	534.8	.201	.193	- 3.9
316.4	.621	452.3	.203	.191	- 6.2
301.1	.624	389.7	.205	.186	- 9.0
289.8	.639	349.9	.205	.186	- 9.3
284.4	.647	325.7	.206	.186	- 9.5
271.4	.674	284.5	.207	.189	- 8.8
261.0	.704	257.4	.208	.192	- 7.4
251.1	.723	231.8	.208	.193	- 7.2
241.4	.752	204.8	.209	.196	- 6.3
225.2	.807	170.7	.210	.202	- 3.5
207.0	.868	138.0	.210	.209	- .6
199.8	.908	126.6	.210	.213	1.7
236.3	.396	202.0	.133	.117	-12.4
226.3	.399	180.6	.133	.116	-12.7
222.7	.408	160.7	.134	.119	-11.2
200.0	.419	123.7	.134	.119	-11.0
188.8	.422	108.1	.134	.119	-11.3
184.3	.422	101.0	.134	.119	-11.6
171.0	.457	85.3	.135	.125	- 7.5
162.7	.469	75.4	.135	.126	- 6.4
151.4	.498	65.4	.135	.131	- 2.9
151.4	.498	65.4	.135	.131	- 2.9
349.4	.372	503.5	.130	.125	- 3.9
333.4	.382	475.0	.131	.126	- 3.5
321.3	.382	423.8	.131	.124	- 5.4
305.1	.379	359.8	.132	.121	- 8.4
294.8	.385	324.3	.133	.121	- 8.5
292.0	.385	310.1	.133	.121	- 9.0
281.9	.385	278.8	.133	.120	-10.3
262.3	.388	223.3	.134	.118	-12.2
259.6	.397	202.0	.135	.120	-11.5
231.7	.408	159.3	.136	.120	-11.7
221.6	.403	142.2	.136	.118	-13.5
210.8	.421	123.7	.136	.121	-11.0
199.6	.436	106.7	.136	.124	- 9.3

Length = 2080 mm. Diameter = 3.94 mm.

ΔT_{sc}	$G/10^6$	P	$q_{exp.}/10^6$	$q_{calc.}/10^6$	deviation
342.5	.664	530.5	.312	.311	- .3
331.6	.675	472.2	.314	.307	- 2.2
316.6	.695	406.8	.316	.305	- 3.7
303.7	.711	355.6	.320	.302	- 5.7
293.9	.735	321.4	.321	.304	- 5.3
287.5	.756	305.8	.322	.308	- 4.5
279.7	.767	288.7	.322	.307	- 4.8
271.3	.793	273.1	.323	.310	- 3.9
265.7	.808	256.0	.323	.312	- 3.7
259.0	.846	241.8	.324	.318	- 1.7
245.7	.899	214.8	.324	.325	.1
235.1	.928	190.6	.327	.326	- .4
223.7	.976	167.8	.327	.332	1.5
207.0	1.043	135.1	.316	.339	7.2
322.2	.680	516.3	.316	.309	- 2.1
315.9	.695	475.0	.317	.309	- 2.5
302.2	.702	413.9	.320	.303	- 5.3
288.5	.737	359.8	.322	.306	- 4.9
274.3	.777	310.1	.323	.310	- 4.2
265.3	.804	281.6	.324	.312	- 3.8
253.3	.849	247.5	.325	.317	- 2.4
242.8	.894	219.0	.326	.323	- .9
230.9	.944	190.6	.327	.328	.4
220.7	.977	169.3	.327	.331	1.1
320.8	.491	497.8	.236	.232	- 1.7
313.4	.486	462.2	.237	.227	- 4.3
310.7	.491	440.9	.238	.228	- 4.4
293.4	.498	372.6	.242	.224	- 7.3
274.0	.516	302.9	.245	.224	- 8.3
264.1	.526	271.7	.246	.224	- 8.8
264.1	.526	270.2	.244	.224	- 8.0
246.6	.543	221.9	.245	.224	- 8.7
236.9	.560	197.7	.246	.226	- 8.1
230.6	.577	182.1	.247	.230	- 6.9
216.7	.579	153.6	.248	.227	- 8.3
207.4	.650	136.5	.248	.245	- 1.2
195.1	.695	116.6	.248	.254	2.4
179.6	.738	95.3	.248	.260	4.7
168.7	.764	82.5	.249	.263	5.7

Length = 1040 mm. Diameter = 3.94 mm.

ΔT_{sc}	$G/10^6$	P	$q_{exp.}/10^6$	$q_{calc.}/10^6$	deviation
324.9	.489	520.6	.235	.233	- .8
317.0	.489	480.7	.237	.230	- 3.1
294.8	.500	395.4	.241	.226	- 6.3
268.9	.517	287.3	.246	.223	- 9.6
255.6	.530	247.5	.248	.223	-10.1
240.1	.552	206.2	.246	.225	- 8.7
230.0	.577	180.6	.247	.230	- 6.9
213.1	.625	145.1	.248	.240	- 3.2
203.4	.650	126.6	.248	.244	- 1.6
343.1	1.091	519.1	.450	.468	4.0
339.1	1.101	499.2	.451	.465	3.1
325.6	1.152	436.6	.454	.461	1.5
319.5	1.157	411.0	.451	.454	- .7
312.1	1.188	391.1	.452	.455	- .7
306.2	1.211	369.8	.453	.454	- .3
298.6	1.239	341.4	.454	.453	- .3
296.1	1.301	332.8	.454	.465	2.4
281.9	1.397	291.6	.456	.472	3.5
330.8	1.135	507.8	.452	.473	4.6
310.0	1.219	411.0	.457	.466	2.0
311.6	1.219	406.8	.458	.466	1.8
297.9	1.275	352.7	.461	.463	.5
287.1	1.360	315.8	.461	.471	2.1
280.3	1.408	293.0	.462	.474	2.6
332.2	.635	530.5	.558	.567	1.7
306.7	.642	455.1	.562	.549	- 2.4
293.0	.658	396.8	.565	.541	- 4.3
281.3	.677	351.3	.568	.538	- 5.2
273.8	.685	324.3	.564	.534	- 5.3
267.8	.705	298.7	.566	.537	- 4.9
261.0	.768	277.3	.567	.564	- .5
249.1	.768	243.2	.570	.551	- 3.5
252.6	.832	200.5	.573	.563	- 1.7
229.0	.832	192.0	.573	.559	- 2.6
216.9	.853	174.9	.574	.557	- 2.7
314.6	.635	505.5	.549	.557	1.5
298.1	.644	426.7	.553	.540	- 2.3
284.9	.661	374.1	.556	.534	- 3.9
263.3	.692	310.1	.561	.529	- 5.7
255.8	.728	274.5	.564	.539	- 4.3
245.0	.753	243.2	.562	.540	- 4.0
232.0	.771	209.1	.564	.535	- 5.2
224.8	.816	192.0	.565	.549	- 2.9
221.0	.831	183.5	.566	.552	- 2.3
349.7	.504	546.2	.479	.475	- .8
339.7	.521	495.0	.483	.484	.4
331.4	.526	456.6	.485	.480	- 1.2
320.4	.529	405.9	.490	.471	- 3.9

Table 1 (Cont.)

ΔT_{sc}	$G/10^6$	P	$q_{exp.}/10^6$	$q_{calc.}/10^6$	deviation
307.3	.540	357.0	.491	.466	- 5.1
297.0	.557	327.1	.493	.469	- 4.9
287.1	.566	297.3	.496	.466	- 5.9
276.3	.571	264.5	.498	.461	- 7.5
262.4	.593	229.0	.498	.463	- 6.9
256.3	.610	213.3	.499	.468	- 6.3
245.5	.629	187.7	.501	.470	- 6.1
229.3	.673	166.4	.502	.483	- 3.6
324.2	.516	503.5	.474	.474	.1
308.3	.533	431.0	.479	.470	- 1.9
294.3	.539	371.2	.483	.461	- 4.6
270.9	.567	290.1	.489	.458	- 6.4
258.3	.596	251.7	.492	.464	- 5.5
250.6	.608	236.1	.493	.465	- 5.6
238.3	.632	204.8	.495	.469	- 5.2
219.2	.703	162.1	.497	.492	- 1.1

Length = 3120 mm. Diameter = 7.76 mm.

ΔT_{sc}	$G/10^6$	P	$q_{exp.}/10^6$	$q_{calc.}/10^6$	deviation
243.9	.462	539.1	.262	.248	- 5.3
222.8	.476	499.2	.263	.244	- 7.0
215.8	.486	475.0	.263	.244	- 7.2
201.8	.493	463.7	.264	.241	- 8.5
193.1	.499	449.4	.264	.240	- 9.1
169.7	.552	361.2	.267	.244	- 8.7
129.2	.564	348.5	.267	.232	-13.2
161.1	.523	413.9	.265	.235	-11.2
206.3	.501	389.7	.266	.241	- 9.7
158.6	.630	270.2	.270	.255	- 5.4
249.3	.284	473.6	.176	.163	- 7.7
239.2	.287	432.4	.177	.162	- 8.7
228.6	.288	399.7	.178	.160	-10.1
208.8	.298	342.8	.179	.159	-10.9
197.5	.299	324.3	.179	.157	-12.1
175.9	.304	298.7	.180	.155	-13.9
169.6	.307	273.1	.180	.154	-14.5
161.5	.319	257.4	.181	.157	-13.1
158.8	.316	253.2	.181	.156	-14.1
139.5	.332	221.9	.180	.157	-13.0
130.0	.343	197.7	.181	.158	-12.6
115.6	.371	172.1	.182	.165	- 9.5
110.5	.392	162.1	.182	.170	- 6.3
103.9	.408	155.0	.182	.174	- 4.5
100.8	.427	150.8	.182	.178	- 1.9
95.9	.439	145.1	.182	.181	- .7
86.0	.482	130.9	.182	.189	3.8
75.0	.549	113.8	.183	.202	10.4
140.9	.313	467.9	.174	.154	-11.2
121.3	.319	402.5	.175	.152	-13.3
103.5	.330	376.9	.175	.151	-13.5
96.1	.330	352.7	.176	.149	-14.9

Table 1 (Cont.)

ΔT_{sc}	$G/10^6$	P	$q_{exp.}/10^6$	$q_{calc.}/10^6$	deviation
88.6	.336	332.8	.176	.150	-15.0
81.0	.335	322.9	.176	.147	-16.4
70.2	.348	295.8	.176	.149	-15.6
70.4	.350	280.2	.177	.149	-15.7
64.6	.335	263.1	.178	.150	-15.8
59.9	.369	243.2	.178	.152	-14.6
52.9	.389	220.5	.176	.156	-11.6
212.2	.178	509.2	.106	.102	- 3.7
203.4	.181	466.5	.107	.103	- 3.5
189.2	.182	406.8	.107	.102	- 4.9
187.7	.184	374.1	.108	.103	- 4.7
182.2	.187	358.4	.108	.104	- 3.7
160.4	.184	291.6	.109	.100	- 8.6
127.6	.189	219.0	.111	.098	-11.2
110.5	.192	196.3	.111	.097	-12.2
102.6	.196	177.8	.112	.099	-11.5
91.8	.196	157.9	.112	.098	-12.8
81.5	.198	142.2	.113	.098	-13.3
69.7	.207	129.4	.114	.101	-11.5
61.6	.209	115.2	.114	.101	-12.0
70.6	.214	95.3	.115	.104	- 9.6
69.5	.215	93.9	.115	.105	- 9.2
61.0	.221	81.1	.116	.106	- 8.6
57.8	.232	74.0	.115	.110	- 4.3
57.1	.238	66.8	.116	.112	- 2.7
54.4	.248	61.2	.116	.115	- .1
60.7	.257	56.9	.116	.120	3.5
58.0	.259	52.6	.116	.120	3.5
61.0	.267	52.6	.116	.123	6.2

Length = 2080 mm. Diameter = 7.76 mm.

ΔT_{sc}	$G/10^6$	P	$q_{exp.}/10^6$	$q_{calc.}/10^6$	deviation
244.3	.436	557.5	.362	.350	- 3.2
233.5	.451	499.2	.364	.347	- 4.6
214.2	.462	416.7	.367	.335	- 8.8
197.6	.479	354.2	.371	.330	-11.0
169.9	.535	268.8	.376	.334	-11.2
178.0	.507	295.8	.374	.328	-12.2
185.8	.487	321.4	.373	.325	-12.6
131.0	.647	197.7	.380	.348	- 8.6
116.6	.714	172.1	.382	.359	- 6.2
129.0	.647	197.7	.380	.347	- 8.9
143.1	.596	234.7	.378	.341	- 9.9
136.3	.621	217.6	.379	.344	- 9.2
119.5	.683	186.3	.381	.351	- 7.8
104.0	.759	160.7	.383	.363	- 5.3
103.3	.772	159.3	.383	.366	- 4.5
101.0	.784	152.2	.384	.367	- 4.4
96.8	.807	146.5	.384	.371	- 3.5
88.7	.841	.132.3	.385	.373	- 3.2
87.8	.857	130.9	.385	.376	- 2.4
84.4	.876	125.2	.385	.377	- 1.9

tive region (from (*b*) to (c)). The general flow picture for the convective region is heat transfer across a thin liquid film with evaporation at its free surface. In order for this region to occur, it is necessary for nucleate boiling to be suppressed. The evidence to sustain this conclusion is discussed in reference [18].[5]

Vanderwater [19] has proposed that the flow region (*b*) heat transfer burnout can be handled by making a material balance on a spray-annular system. The burnout condition is taken to be the disappearance of the liquid film. It is assumed that there is a transfer of liquid between the film and the core which involves droplet diffusion and entrainment. By making an assumption about the initial liquid distribution, the problem is solved by an integration leading to the burnout condition of no liquid remaining in the annular film.

Starting with the basic material balance of Vanderwater, attempts were made to ascertain whether the burnout equation could be derived utilizing information which was not obtained from the burnout experiments. There are three fundamental quantities needed in the material balance method: The initial liquid distribution; the initiation of the region of applicability; and the liquid transfer rates, or net liquid transfer rate. Obtaining these quantities would then serve to unify the burnout problem with other two-phase flow problems.

[5] Numbers in brackets designate Additional References at end of discussion.

The problem of determining the region of applicability of the method is directly related to the problem of determining the initiation of the core-film flow. An investigation of the conditions indicated that a simple criterion could be employed utilizing the gas velocity, V_a, with values between 1 and 10 ft/sec. The inlet quality, at the position where the model is applicable, is

$$x_a = \rho_g V_a 3600/G$$

where ρ_g is the vapor density, and G is the mass flow rate in lb/hr-ft^2.

The evidence concerning the initial liquid distribution indicated that the bulk of the liquid is in contact with the annular liquid film, unless a two-phase feed is used. This analysis is limited to the use of a subcooled feed. The start of the core-film flow is handled by assuming a certain liquid fraction, f, represents the fraction of the liquid flowing in the annular film. The mass liquid flow in the film at the start of the application of the model is

$$W_{fa} = \frac{\pi D^2}{4} G(1 - x_a)f$$

where D is the diameter of the test section. (The Becker burnout data are for flow of boiling water in vertical round ducts with constant heat flux with length.)

Table 1 (Cont.)

ΔT_{sc}	$G/10^6$	P	$q_{exp.}/10^6$	$q_{calc.}/10^6$	deviation
79.7	.909	118.1	.385	.381	- 1.0
78.8	.920	113.8	.385	.381	- .9
79.0	.936	110.9	.385	.385	.0
77.2	.942	108.1	.385	.385	- .1
252.4	.434	593.1	.365	.357	- 2.1
249.8	.431	586.0	.365	.353	- 3.2
235.4	.453	527.7	.367	.353	- 3.7
218.5	.445	470.8	.369	.333	- 9.7
173.9	.507	359.8	.374	.333	-11.0
164.9	.516	382.6	.373	.336	-10.1
153.7	.466	445.2	.371	.313	-15.5
162.2	.483	416.7	.372	.322	-13.2
124.0	.558	293.0	.379	.323	-14.7
126.2	.536	322.9	.374	.319	-14.9
269.8	.427	547.6	.365	.354	- 2.9
259.0	.445	506.3	.366	.356	- 2.8
263.5	.428	536.2	.365	.351	- 3.9
247.1	.448	483.7	.368	.347	- 5.7
230.8	.442	433.8	.369	.333	- 9.6
238.5	.442	477.9	.367	.342	- 6.9
243.7	.442	506.3	.366	.347	- 5.0
228.2	.456	438.1	.369	.341	- 7.6
208.4	.459	396.8	.371	.329	-11.1
203.8	.467	385.4	.371	.330	-11.0
216.5	.463	406.8	.371	.336	- 9.4
191.7	.469	389.7	.371	.326	-12.1
184.3	.481	369.8	.372	.327	-12.0
174.6	.481	352.7	.373	.321	-13.9
168.5	.490	337.1	.374	.320	-14.2
153.7	.519	300.1	.376	.323	-14.1
138.1	.561	263.1	.378	.328	-13.2
120.8	.622	230.4	.380	.337	-11.3
118.4	.622	238.9	.380	.337	-11.2
107.5	.670	211.9	.382	.343	-10.1
101.7	.702	202.0	.382	.348	- 9.0
94.3	.737	186.3	.383	.352	- 8.3
85.9	.772	180.6	.384	.355	- 7.5
80.5	.809	169.3	.385	.360	- 6.4
259.4	.337	496.4	.299	.283	- 5.5
260.1	.337	520.6	.299	.285	- 4.9
264.1	.341	570.3	.297	.293	- 1.5
241.2	.355	472.2	.301	.287	- 4.4
228.2	.354	415.3	.302	.278	- 8.1
216.0	.355	372.6	.304	.272	-10.6
213.1	.357	386.9	.304	.273	-10.2
191.3	.357	314.3	.303	.261	-13.8
160.7	.392	244.6	.307	.265	-13.7
134.6	.436	199.1	.309	.272	-11.9
128.2	.453	187.7	.309	.276	-10.7
122.6	.467	179.2	.310	.280	- 9.6
109.1	.509	156.5	.312	.290	- 7.2
106.0	.518	153.6	.312	.291	- 6.7
98.6	.549	143.7	.312	.298	- 4.5
91.1	.561	136.5	.312	.299	- 4.4
75.6	.618	116.6	.306	.308	.5

Table 1 (Cont.)

ΔT_{sc}	$G/10^6$	P	$q_{exp.}/10^6$	$q_{calc.}/10^6$	deviation
72.2	.653	112.4	.307	.315	2.8
68.0	.796	101.0	.307	.348	13.4
79.7	.803	96.7	.307	.357	16.3
262.8	.351	510.6	.307	.295	- 3.8
251.1	.349	458.0	.308	.286	- 7.3
239.9	.351	415.3	.311	.280	- 9.9
233.6	.355	392.6	.312	.279	-10.5
227.9	.361	371.2	.314	.279	-11.1
211.5	.365	320.0	.316	.273	-13.4
198.5	.378	283.0	.317	.273	-13.8
212.4	.366	347.0	.314	.276	-12.3
217.6	.358	367.0	.314	.274	-12.7
204.3	.365	341.4	.309	.272	-12.1
193.1	.380	310.1	.311	.274	-11.7
183.6	.387	283.0	.312	.273	-12.5
176.9	.392	266.0	.313	.272	-13.2
166.3	.401	246.1	.314	.271	-13.6
160.6	.413	233.3	.315	.274	-12.9
151.9	.432	220.5	.316	.279	-11.8
139.3	.450	199.1	.317	.280	-11.5
131.2	.472	190.6	.317	.285	-10.2
110.9	.554	153.6	.319	.306	- 4.0
102.4	.577	143.7	.317	.309	- 2.6
279.2	.245	568.9	.222	.222	- .3
272.7	.246	531.9	.224	.220	- 1.8
256.0	.246	453.7	.227	.214	- 5.6
247.9	.253	418.2	.229	.216	- 5.5
241.4	.251	392.6	.230	.212	- 7.6
230.9	.256	355.6	.231	.212	- 8.0
207.7	.257	291.6	.234	.206	-11.9
200.9	.257	271.7	.234	.204	-13.0
190.4	.262	250.3	.235	.204	-13.5
179.6	.263	226.1	.236	.201	-14.9
163.1	.274	192.0	.231	.203	-12.3
174.4	.267	236.1	.230	.202	-12.0
124.6	.284	210.5	.231	.199	-13.9
139.0	.296	162.1	.233	.209	-10.1
151.0	.277	194.9	.232	.201	-13.0
145.4	.282	184.9	.232	.203	-12.5
134.3	.299	162.1	.233	.209	- 9.9
119.5	.318	142.2	.234	.215	- 7.9
112.1	.332	132.3	.234	.220	- 6.0
105.7	.340	126.6	.234	.222	- 5.3
97.2	.355	122.3	.236	.226	- 4.1
93.8	.364	120.9	.236	.228	- 3.1
82.3	.392	113.8	.236	.236	.2
74.2	.408	102.4	.236	.240	1.7
218.7	.262	357.0	.234	.213	- 8.9
214.0	.262	338.5	.235	.212	-10.0
207.4	.263	314.3	.236	.210	-11.0
196.0	.266	281.6	.237	.208	-12.2
184.9	.270	253.2	.207	.207	.0
169.7	.273	217.6	.240	.204	-14.8
152.5	.291	182.1	.241	.210	-13.0
144.0	.299	162.1	.256	.212	-10.2

Table 1 (Cont.)

ΔT_{sc}	$G/10^6$	P	$q_{exp.}/10^6$	$q_{calc.}/10^6$	deviation
130.3	.312	146.5	.237	.215	- 9.1
249.3	.206	409.6	.188	.181	- 3.7
241.2	.204	374.1	.189	.178	- 5.9
227.2	.204	328.6	.190	.174	- 8.1
210.4	.204	283.0	.191	.171	-10.7
184.0	.206	226.1	.190	.166	-12.7
176.2	.207	203.4	.191	.165	-13.5
154.1	.214	172.1	.192	.166	-13.5
142.9	.212	156.5	.192	.163	-15.1
124.6	.226	129.4	.193	.168	-12.7
105.5	.240	118.1	.191	.173	- 9.7
102.8	.237	116.6	.191	.170	-11.1
97.9	.239	108.1	.192	.171	-11.0
87.3	.254	96.7	.192	.177	- 7.8
81.0	.266	91.0	.189	.182	- 3.8
64.1	.287	75.4	.189	.188	- .8

The liquid transfer function is more difficult to handle. Emphasis may be given to either the droplet diffusion or to the entrainment. Our present analysis assumes that the net liquid transfer between the film and the core can be treated as only an entrainment function. Rates of entrainment were determined for the Harwell adiabatic air-water data [20], and the functions reflected the increase in entrainment with length, total liquid rate, and total gas rate. In the applications to the burnout data, it was found that the effects of subcooling and heated length were not correctly predicted. The conclusion reached is that the entrainment rate should also be a function of the heat flux. There are no data available on the rate of entrainment in a system which is sustaining a heat flux, and so it became necessary to assume an empirical form for this function. The rate of entrainment was taken as

$$E = KW_f/\pi D \quad \text{with} \quad K = \alpha(q/\lambda)^m$$

where

E = rate of entrainment
W_f = film flow rate
α = constant
m = const; SC = subcooling no. = $c_p\,\Delta T_{SC}/\lambda$
$q(/\lambda)$ = evaporative mass flux
L = length, L_T = total heated length

The material balance on the liquid flowing in the film becomes

$$\frac{dW_f}{dL} = -\pi D\left\{\frac{\alpha(q/\lambda)^m W_f}{\pi D} + q/\lambda\right\}$$

This equation states that the rate of change of film flow with length is equal to the amount of liquid removed by entrainment and by evaporation. The solution employs the boundary conditions,

$$W_f = W_{fa} \quad \text{at} \quad x = x_a$$

$$W_f = 0 \quad \text{at} \quad x = x_{BO}$$

and yields

$$(x_{BO} - x_a) = \frac{1}{\alpha}\left(\frac{L_T}{x_{BO} + SC}\right)^{m-1}\left(\frac{4}{DG}\right)^m \ln\left\{1 + (1 - x_a)f\alpha\left(\frac{x_{BO} + SC}{L_T}\right)^{m-1}\left(\frac{DG}{4}\right)^m\right\}$$

The value for m was inferred from the Becker-Persson paper, by using $f(x_{BO}, p) = 1/qG^{1/2}$ with the heat flux tending to be proportional to the mass flow rate for subcooled feeds. The use of $m = 1.5$ appears reasonable. The value for α was obtained using the first 360 data points furnished by Dr. Becker. A pressure dependency was noted and the following choices were made:

$\alpha = 3000 - 4P$, where P is pressure in psia
$V_a = 6$ ft/sec
$f = 0.95$
$m = 1.5$

The results of this correlation are shown in Table 1. It can be seen that most of the data are predicted within 10 percent (using the heat flux as the quantity being compared). The range of the data covered in this table is quite extensive: pressure varied from 50 to 600 psia; subcooling varied from 350 to 50 deg F; mass flow rates from 0.15 to 1.5 $\times$ 10^6 lb/hr-ft^2; lengths of 3120, 2080, and 1040 mm; and diameters of 3.94 and 7.76 mm. In view of the range of variables (and the fact that no attempt was made at optimizing the parameters), it is concluded that a successful correlation procedure is outlined in this note.

This correlation was developed by assuming droplet diffusion to be negligible, and that the burnout is determined from a liquid film flow from which liquid is removed by entrainment and evaporation. The fact that other models based upon a completely different flow picture (i.e., droplet diffusion dominated burnout), can also yield burnout correlations simply indicates that the relative merits of the various burnout models cannot be judged on the basis of the ability to correlate burnout data alone. The judgment should include more basic studies of the flow conditions existing in the burnout systems with emphasis on the three fundamental quantities listed at the start of this note.

Additional References

18 T. M. Grace, "The Mechanism of Burnout in Initially Sub-Cooled Forced Convective Systems," PhD thesis, Dept. Chem. Engr., Univ. of Minnesota, December, 1963.

19 R. G. Vanderwater, "An Analysis of Burnout in Two-Phase Liquid Vapor Flow," PhD thesis, Dept. Chem. Engr., Univ. of Minnesota, December, 1956.

20 L. E. Gill and G. F. Hewitt, "Further Data on the Annular Flow of Air/Water Mixtures in a 1¼ in. Bore Perspex Tube," AERE—R3935, 1962; L. E. Gill, G. F. Hewitt, and J. W. Hitchon, "Sampling Probe Studies of Gas Core in Annular Two-Phase Flow. Part I. The Effect of Length on Phase and Velocity Distribution," AERE—R3954, 1962; and L. E. Gill, G. F. Hewitt, and P. M. C. Lacy, "Sampling Probe Studies of the Gas Core in Annular Two-Phase Flow. Part II. Studies of the Effect of Phase Flow Rates on Phase and Velocity Distributions," AERE-R3955, 1963.

Authors' Closure

We are surprised that Dr. Fauske questions the fact that our analysis shows the burnout conditions to be independent of the inlet subcooling and the L/d-ratio. Figs. 9 and 10, where the deviations between measured and predicted burnout enthalpies are plotted versus the inlet subcooling temperature and the L/d-ratio, show completely random scatters indicating the non-existence of length or inlet temperature effects.

Additional verification of the negligible L/d and inlet subcooling effect has been obtained recently in our laboratory, carrying out measurements at pressures between 40 and 100 kg/cm^2 and with test sections of 10 mm inner dia and of 1000, 1500, 2000, 2500, 3000, and 3500 mm heated length. A typical example of the results is shown in Fig. 15, where the measured burnout qualities for a heat flux of 200 W/cm^2 and a pressure of 71 kg/cm^2 are plotted versus the mass velocity. Despite the rather large ranges of subcooling temperatures and test section lengths covered, no effects of these parameters are visible in the figure.

Furthermore, Fig. 2, which represents the analytical results and compares burnout conditions for zero subcooling and maximum possible subcooling, indicates that up to 70 kg/cm^2 the maximum difference is 5 percent and at 140 kg/cm^2 differences up to 8 percent are encountered. We should like to point out here that the paper clearly states that both sets of curves in Fig. 2 were established using the same values for ϵ and b. Dr. Fauske's remarks that the heat balance has been violated by neglecting N_{sc}, and that the violation has been compensated for by using a new set of values for ϵ and b are therefore misleading.

Our statement, while discussing equations (9) and (10), that when the burnout conditions in a particular duct are considered, the solution obtained from the correlation must be checked in order to avoid a violation of the heat balance, applies to any correlation, empirical or analytical and independently of its origin. If for instance, x, $\dot{m}/F$, Δt_{sub}, and p are given for a particular test section and we compute the burnout heat flux by means of the correlation, the solution will almost certainly violate the heat balance. Therefore, the problem should be solved by leaving two of the variables unspecified, for instance q/A and x, and determining these variables simultaneously, using the two available equations, the heat balance equation, and the burnout correlation.

As regards the discussion by Dr. Grace and Professor Isbin, we find it very encouraging that their rather simple flow model yields an expression which correlates our burnout data quite accurately. However, the 360 data points which they used comprised only heat fluxes between 34 and 180 W/cm^2 and steam qualities between 0.40 and 0.98. Our complete burnout studies include so far about 4000 round duct measurements. The present paper dealt with about 2500 of these measurements, covering heat fluxes from 50 to 620 W/cm^2 and steam qualities from 0.13 to 0.98.

It would therefore be of great interest to compare Grace and Isbin's and the present correlation, using the experimental results given in the paper. However, too much time would be needed in order to comply with the deadline for submitting this closure, but the comparison just referred to has been performed using 21 arbitrarily selected measurements obtained at a pressure of 30 kg/cm^2 and covering heat fluxes up to 510 W/cm^2.

Table 2 shows the results of the comparison, and in Fig. 16 the computed values of the burnout heat flux are plotted versus the experimental values. One observes that up to 450 W/cm^2 the predictions of Grace and Isbin deviate from -12 to $+5$ percent. The rms error was 8.5 percent, which indeed should be considered satisfactory, especially in view of their rather simple flow model.

The predictions of the present analysis are, except for a few points, within ± 5 percent of the measured values and the rms error is 4.1 percent.

One should also note that since in Grace and Isbins' correlation, the pressure correction term $3000 - 4p$ becomes negative for pressures higher than 750 psia; this term needs to be modified before the equation is applied to higher pressures, where its accuracy also still needs testing.

Now, one might find it surprising that the average scatter for the arbitrarily selected points used in Fig. 16 is much smaller than the scatter which seems to be present in Fig. 6, where all our data obtained at 30 kg/cm^2 are included. The reason for this apparent inconsistency is that the real deviations between the measured values and the correlation cannot be estimated from Fig. 6 without considering the heat balance equation. This important fact is actually the key to a sound and correct treatment of the burnout problem. Consider the example given in Fig. 17, where the correlation is compared with one of our measurements, which is described by the following parameters.

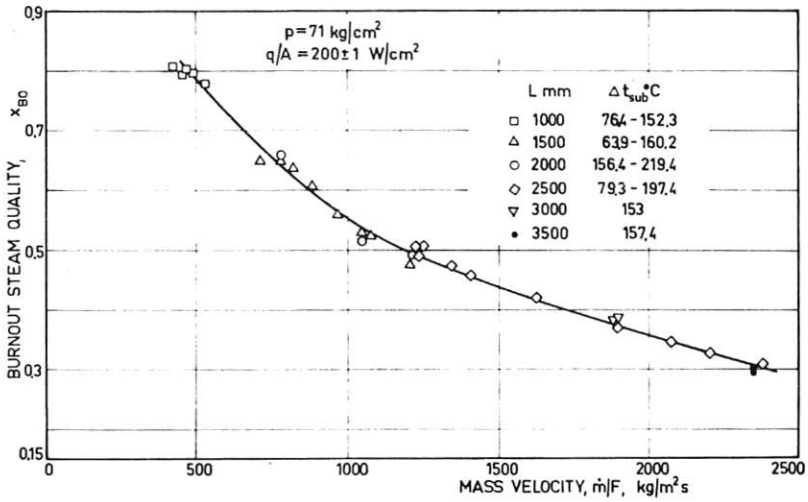

Fig. 15 Measured burnout conditions

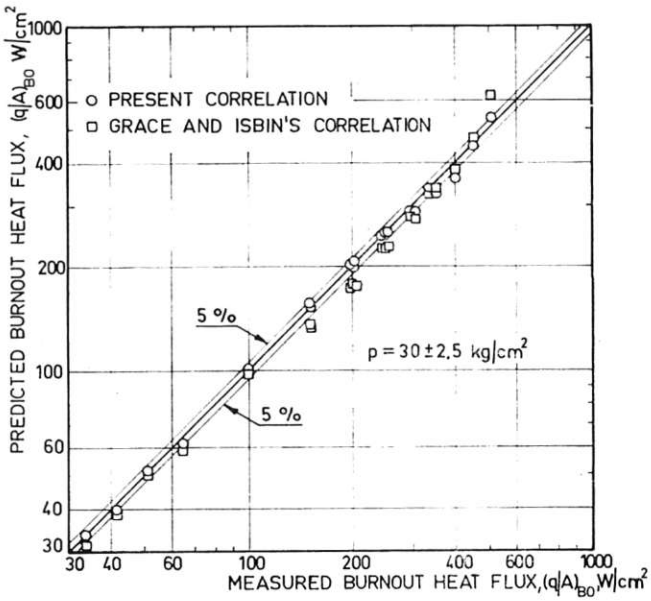

Fig. 16 Comparison between predicted and measured burnout conditions

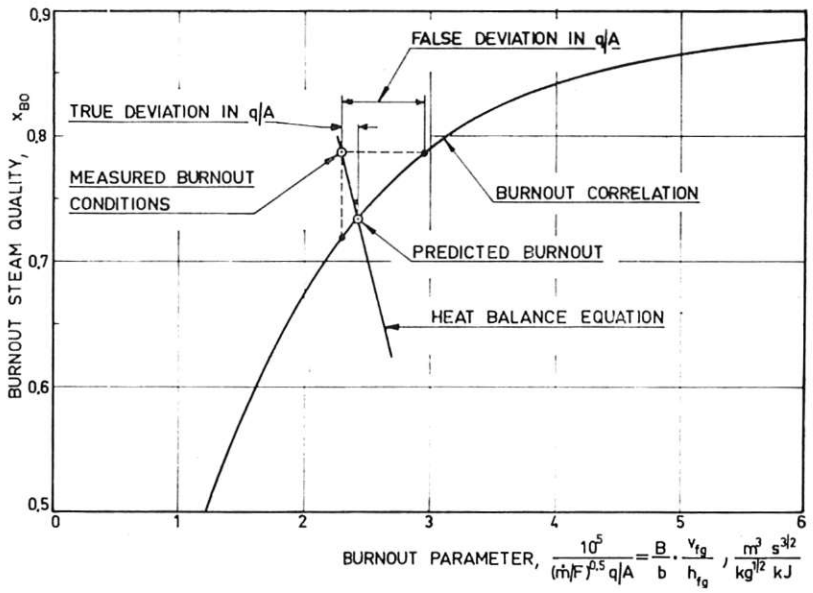

Fig. 17 Comparison between predicted and measured burnout conditions

Table 2 Comparison of burnout correlations

Measured burnout values			Grace and Isbin			Present correlation		
Run No	x_{BO}	$(q/A)_{BO}$ W/cm²	x_{BO}	$(q/A)_{BO}$ W/cm²	Error in q/A percent	x_{BO}	$(q/A)_{BO}$ W/cm²	Error in q/A percent
1.196	0.9589	33.8	0.876	31.5	−6.8	0.900	33.6	−0.6
1.41	0.9707	41.4	0.865	38.4	−7.4	0.895	39.5	−4.8
1.18	0.9223	64.1	0.801	58.4	−8.9	0.872	61.9	−3.4
1.545	0.8799	51.3	0.905	52.4	+2.1	0.899	51.6	+0.6
2.563	0.8654	99.4	0.821	98.2	−1.2	0.870	100.6	+1.2
2.394	0.6474	149.9	0.559	136.2	−9.1	0.700	156.7	+4.5
2.504	0.7310	150.5	0.630	136.0	−9.6	0.760	153.2	+1.7
2.1231	0.5561	196.7	0.447	175.6	−10.7	0.580	202.1	+2.9
2.409	0.4576	201.4	0.385	179.5	−10.9	0.480	207.7	+3.1
2.524	0.6029	201.6	0.498	177.7	−11.8	0.590	199.0	−1.3
2.1522	0.5652	244.5	0.498	229.0	−6.3	0.575	248.0	+1.5
2.1364	0.5063	250.0	0.422	228.0	−8.8	0.505	250.0	0
2.1499	0.5585	253.6	0.458	228.6	−9.9	0.540	249.7	−1.4
2.1515	0.4476	296.9	0.417	279.5	−5.9	0.455	292.5	−1.5
2.1681	0.5280	300.0	0.475	264.0	−12.0	0.530	278.0	−7.3
2.693	0.4125	303.5	0.358	277.5	−8.6	0.380	288.0	−5.1
2.1683	0.4470	332.0	0.402	312.0	−6.0	0.431	323.5	−2.6
2.864	0.3843	350.8	0.358	335.0	−4.5	0.350	328.0	−6.4
2.121	0.4063	401.3	0.400	381.0	−5.1	0.350	352.5	−12.2
2.157	0.1806	452.9	0.218	474.0	+4.8	0.180	443.3	−2.1
2.1721	0.2646	510.5	0.421	614.0	+20.3	0.310	541.5	+6.1

L	d	p	Δt_{sub}	
1250 mm	10 mm	31.3 kg/cm²	162 deg C	
		$\dot{m}/F$	$(q/A)_{BO}$	x_{BO}
		472 kg/m²s	201 W/cm²	0.792

If the measured $(q/A)_{BO}$ is compared with the q/A-value corresponding to point M on the curve representing the correlation, a deviation of 24 percent is obtained. However, point M does not satisfy the heat balance equation for the test section and is therefore insignificant. The correct prediction is established as the intersection of the curves representing the correlation and the heat balance equation. One should note that along the latter curve all parameters, except x and q/A, are identical with the measured values. The deviation between the measured and the predicted burnout heat flux now becomes 5 percent instead of the apparent and false deviation of 24 percent. The scatter in terms of x_{BO} or h_{BO} should also be determined in the same manner.

We regret that this treatment of the scatter was not more clearly described in the paper. However, we stressed the importance of considering simultaneously the heat balance equation and the correlation, stating that equations (9), (10), and (11) and the curves for ϵ and b in Fig. 3 define the burnout conditions in round ducts.

We should also like to mention that the predicted values for h_{BO} in Fig. 8 correspond to point N in Fig. 17. Our conclusion that the deviations between experimental and theoretical results were less than ±10 percent was therefore conservative. Reverting to Fig. 16 it seems more reasonable to expect that the scatter for our complete experimental study is less than ±5 percent compared to the predicted values and that the rms error is 3–5 percent.

The agreement between predicted and measured burnout conditions is therefore excellent, and we recommend the use of our equation in the ranges of variables covered by the experimental investigation, which since the submission of the paper has been extended to comprise the following ranges of variables.

Diameter	d	3.94–13.06 mm
Heated length	L	600–3500 mm
L/d-ratio	L/d	46–780
Pressure	p	6–100 kg/cm²
Inlet subcooling	Δt_{sub}	30–220 deg C
Mass velocity	$\dot{m}/F$	120–3500 kg/m²s
Heat flux	q/A	35–515 W/cm²
Steam quality	x	0.05–0.98

However, we would like to point out that for steam qualities higher than about 90 percent some mathematical difficulties arise, since the term inside the third logarithm in equation (10) becomes negative. A fair approximation is then obtained by a series expansion of this logarithm, and using only the first term of the series. This limitation of the theoretical result, however, is not serious since for steam qualities above 90 percent only small errors are possible and a correlation stating that $x_{BO} = 0.95$ would in this region together with the heat balance equation predict burnout heat fluxes within ±5 percent. The mentioned mathematical difficulties can also be avoided by letting the re-entrainment coefficient, ϵ, be a function of both pressure and steam quality. At present we are using our recent data in the pressure range from 40–100 kg/cm² to determine more accurate values for ϵ and b in this pressure region.

Finally, we would like to thank the reviewers for their valuable and interesting comments, and express our appreciation of the flow model presented by Dr. Grace and Professor Isbin, which in spite of its simplicity resulted in a useful correlation.