Research Article

Application of the Critical Heat Flux Look-Up Table to Large Diameter Tubes

M. El Nakla,¹ M. Habib,¹ W. Ahmed,¹ A. Al-Sarkhi,¹ R. Ben Mansour,¹ and M. Y. Al-Awwad²

¹ Mechanical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

² Consulting Services Department, Saudi Aramco Oil Company, Dhahran 31261, Saudi Arabia

Correspondence should be addressed to M. El Nakla; elnakla@kfupm.edu.sa

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The critical heat flux look-up table was applied to a large diameter tube, namely 67 mm inside diameter tube, to predict the occurrence of the phenomenon for both vertical and horizontal uniformly heated tubes. Water was considered as coolant. For the vertical tube, a diameter correction factor was directly applied to the 1995 critical heat flux look-up table. To predict the occurrence of critical heat flux in horizontal tube, an extra correction factor to account for flow stratification was applied. Both derived tables were used to predict the effect of high heat flux and tube blockage on critical heat flux occurrence in boiler tubes. Moreover, the horizontal tube look-up table was used to predict the safety limits of the operation of boiler for 50% allowable heat flux.

1. Introduction

Critical heat flux (CHF) is a phenomenon corresponding to the point where a continuous liquid contact cannot be maintained at the heated surface. Strictly speaking, this particular term refers to the heat flux corresponding to the occurrence of the phenomenon. Other terms often used are burnout, dryout, boiling crisis, and departure from nucleate boiling (DNB).

CHF results in sudden drop in heat transfer rate between the heated surface and the coolant. Beyond CHF, a small increase in heat flux leads to large increase in surface temperature for a heat-flux-controlled surface (e.g., electric heaters), and a small increase in surface temperature leads to decrease in heat flux for a temperature-controlled surface (e.g., steam condensers). This could lead to overheating damaging of the surface, corrosion in the CHF region, and reduction in the operating efficiency.

Various prediction methods for CHF have been proposed during the past 60 years. The earliest prediction methods were primarily empirical [1, 2]. These crude empirical correlations lacked any physical basis and had a limited range of application. Subsequently, a large number of phenomenological equations or physical models for CHF were developed; many

of these models were subsequently used in the safety analysis of nuclear reactors, boilers, and steam generators. Physical models, however, depend on the mechanisms controlling the CHF, which are flow-regime dependent. Flow regimes change significantly during a typical transient, and this necessitates the use of a combination of different models, equations, or correlations for CHF in safety analysis codes. Since most empirical CHF correlations and models have a limited range of application, the need for a more generalized technique is obvious. Hence, look-up tables (LUTs) for predicting CHF were subsequently derived. As a basis of the generalized technique, the common local-conditions hypothesis was used; that is, it was assumed that the CHF for a water-cooled tube with a fixed tube diameter is a unique function of local pressure (P), mass flux (G), and thermodynamic quality (x).

The CHF-LUT is basically a normalized water CHF data bank for vertical tubes with 8 mm in tube diameter. Compared to other available prediction methods, the LUT approach has the following advantages: (i) greater accuracy, (ii) wider range of application, (iii) correct asymptotic trend, (iv) requires less computing time, and (v) can be updated if additional data become available. The greatest potential for the CHF-LUT approach is its application in predicting the consequences of pipe breakage in reactors and boilers.

The following sections describe the background, the derivation, and the application of the CHF-LUT to predict CHF occurrence in vertical and horizontal large-diameter tubes. The CHF-LUTs specifically for 67 mm diameter tubes were generated in this work covering wide range of flow conditions of pressure, mass flux, and thermodynamic quality.

2. Predicting CHF in Vertical Tube

2.1. Analysis. Groeneveld et al. [3] combined the CHF data of both Atomic Energy of Canada Limited and the Institute of Physics and Power Engineering in the Russian Republic (a total of over 30 000 points) and updated the look-up table for tubes. The new table (1995 CHF-LUT) provides a better prediction accuracy (root-mean-squared error of 7.82% for dryout power prediction against 25,630 CHF experimental data points from 49 different experiments) than other look-up tables and correlations over the complete range of flow conditions. In addition, Groeneveld et al. [3] employed a multidimension smoothing procedure of Huang and Cheng [4], which has eliminated several irregularities in the parametric trends.

The 1995 tube CHF-LUT as well as the earlier versions of the LUT have been assessed extensively. The most recent assessment was made by Baek et al. [5] using their database. Their assessment confirms the error statistics reported by Groeneveld et al. [3] and the improved prediction capability compared with previous versions of the table. Earlier assessments by Smith [6] and the developers of the RELAP code indicated the suitability of the table look-up approach and resulted in its use in system codes such as CATHARE [7], THERMOHYDRAULIK [8], and RELAP [9]. Considering all of these reasons, the 1995 CHF-LUT was selected as the base of the current analysis for predicting CHF in vertical tubes.

The 1995 CHF-LUT was built for water upward flow in 8 mm diameter vertical tube. To use the table for other tube diameters, Groeneveld et al. [3] derived a diameter correction factor (K_{dia}) such that for $0.002 \text{ m} \leq D_{\text{hy}} \leq 0.025 \text{ m}$,

$$K_{\text{dia}} = \left(\frac{0.008}{D_{\text{hy}}} \right)^{0.5}, \quad (1)$$

and for $D_{\text{hy}} > 0.025 \text{ m}$,

$$K_{\text{dia}} = 0.57. \quad (2)$$

This correction factor can be multiplied by the CHF values of 1995 CHF-LUT to get the corresponding CHF for non-8 mm diameter tube as follows:

$$\text{CHF}_{\text{ver}} = K_{\text{dia}} \cdot \text{CHF}_{\text{ver}, 8 \text{ mm}}. \quad (3)$$

2.2. Discussion. The 1995 CHF-LUT along with (2) (for $D_{\text{hy}} = 0.067 \text{ m}$) were used to derive a modified LUT suitable for the current application. Table 1 shows the derived LUT using (3) and the 1995 CHF-LUT. This table has flow-condition limits other than the original table to suit the current application. The ranges of flow parameters are limited to pressures of 100–7000 kPa, mass fluxes of $100\text{--}2000 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, and qualities of $-0.15\text{--}0.8$.

Figure 1 shows pressure effect on the predicted CHF value at low, low-to-moderate and moderate, mass fluxes. At low mass flux (Figure 1(a)), there is no apparent effect of pressure on CHF. At low-to-moderate and moderate mass fluxes (Figures 1(b) and 1(c)), however, evident pressure effect was observed. For the low-to-moderate quality region ($< \sim 0.35$), which is the region of interest, CHF increases with decreasing pressure. This is similar to what is reported in the literature (e.g., [10]).

The effect of mass flux on CHF is shown in Figure 2. Similar to pressure effect, CHF increases with increasing mass flux then starts decreasing. The decrease in this region in CHF is due to the vapor generation rate and the interaction between vapor and liquid at the interface (see also [10]).

As an example of the application of the LUT approach on predicting the safe operation of boilers, consider the results shown in Table 2. For the base case, which represents the normal operating conditions of an actual boiler, CHF is unlikely to occur because it is 32 times higher than the operating heat flux. When the operating heat flux is increased by four times, the exit quality increased which results in reduction in CHF value. Even with that increase in operating heat flux, the CHF value is still much higher (6 times) than the operating heat flux. The final case is with 90% blockage of the tube which will result in reduction in mass flux and increase in quality. Table 2 shows that even with this amount of blockage it is still unlikely for CHF to occur.

3. Predicting CHF in Horizontal Tube

3.1. General Considerations. CHF prediction for a horizontal flow differs from that of vertical flow. For horizontal flow, flow stratification effect appears as a result of gravitational forces. For instance, in annular flow regime of vertical upward flow, the liquid film is said to be uniformly distributed (has the same thickness) on the tube wall. In the same flow regime of horizontal flow, the liquid film has greater flow thickness at the bottom of the tube while it is thinner on the upper part (Figure 3). This will dramatically decrease the heat flux value at which CHF occurs specially at low mass fluxes and large tube diameters ($G < 2000 \text{ kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, $D_{\text{hy}} > 25 \text{ mm}$) [3]. At high mass fluxes and smaller tube diameters, CHF is predicted for horizontal tubes in the same manner as in vertical tubes.

To improve the value of CHF for horizontal flow, Collier and Thome [10] suggested the use of flow enhancers such as twisted tape tube inserts and replacing the tubes by microfinned tubes (see Figure 4). For twisted tapes, heat transfer augmentation ratios are typically in the range from 1.2 to 1.5 while the two-phase pressure drop ratios are often as high as 2.0 because the tape divides the flow area into two smaller areas with smaller hydraulic diameters. By using the microfinned tube, heat transfer enhancements can be as high as three to four times for horizontal flow with low mass fluxes. Two-phase pressure drop ratios range from 1.0 at low mass fluxes up to a maximum of 1.5 at high mass fluxes.

TABLE 1: CHF-LUT for vertical up-flow in 67 mm diameter tube.

P (kPa)	G ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	Quality, x (—)													
		−0.15	−0.10	−0.05	0.00	0.05	0.10	0.15	0.20	0.30	0.40	0.50	0.60	0.70	0.80
		Critical heat flux, CHF ($\text{kW}\cdot\text{m}^{-2}$)													
100	100	2967	2351	1677	1110	661	648	640	631	618	610	591	548	426	314
100	500	2999	2454	2148	1826	1163	1076	1073	1069	983	921	834	677	429	318
100	1000	3071	2637	2354	2010	1441	1303	1300	1260	1156	943	930	817	485	244
100	1500	3096	2698	2403	2055	1512	1383	1371	1306	1188	1058	1058	910	478	198
100	2000	3097	2701	2404	2061	1535	1418	1394	1330	1171	1093	1035	836	384	104
1000	100	3240	3010	2765	2433	1930	1595	1511	1443	1306	1163	971	748	736	713
1000	500	4176	4091	4053	4017	3886	3289	2904	2656	2198	1302	946	590	470	437
1000	1000	4178	4099	4061	4003	3822	3246	2874	2641	1860	1160	864	546	337	258
1000	1500	4189	4121	4077	3997	3764	3153	2844	2521	1845	887	530	363	234	211
1000	2000	4232	4150	4099	3997	3649	2962	2690	2510	1792	783	406	308	196	78
2000	100	3301	3132	2944	2658	2140	1796	1703	1629	1487	1330	1160	998	920	809
2000	500	4241	4195	4200	4181	4079	3640	3276	2941	2469	1618	1420	1077	760	595
2000	1000	4243	4201	4173	4142	4032	3574	3206	2922	2127	1457	1178	822	523	365
2000	1500	4254	4215	4168	4118	3948	3475	3126	2698	2003	1211	758	489	296	248
2000	2000	4293	4232	4174	4078	3740	3198	2860	2540	1889	1041	548	327	204	133
3000	100	3361	3254	3123	2882	2349	1996	1896	1816	1668	1496	1349	1249	1104	905
3000	500	4306	4298	4347	4344	4273	3990	3648	3226	2740	1933	1895	1565	1049	752
3000	1000	4309	4302	4285	4282	4243	3902	3539	3203	2394	1755	1492	1097	708	473
3000	1500	4319	4309	4258	4239	4133	3797	3409	2875	2161	1534	985	616	357	284
3000	2000	4355	4313	4248	4160	3832	3435	3030	2569	1986	1299	690	347	213	188
4000	100	3315	3215	3097	2885	2362	2027	1933	1853	1706	1547	1380	1280	1164	953
4000	500	4114	4093	4115	4093	3959	3629	3333	3089	2678	2100	1946	1649	1226	880
4000	1000	4134	4097	4064	4021	3862	3565	3277	3014	2384	1860	1626	1137	762	531
4000	1500	4162	4109	4041	3955	3713	3414	3101	2728	2113	1617	1101	648	439	398
4000	2000	4212	4136	4003	3821	3416	3079	2770	2420	1907	1378	725	364	292	279
5000	100	3268	3177	3071	2887	2374	2057	1971	1890	1745	1598	1411	1311	1224	1001
5000	500	3923	3887	3883	3841	3645	3268	3019	2951	2615	2266	1997	1733	1402	1008
5000	1000	3958	3893	3844	3759	3481	3227	3015	2825	2375	1965	1759	1178	817	589
5000	1500	4004	3910	3823	3671	3294	3031	2792	2582	2065	1700	1216	681	520	512
5000	2000	4069	3958	3758	3483	2999	2724	2511	2271	1827	1457	759	381	371	371
6000	100	3173	3097	3006	2835	2325	2012	1925	1845	1691	1553	1386	1045	939	861
6000	500	3694	3627	3600	3569	3407	3061	2853	2749	2470	2173	1977	1638	1353	933
6000	1000	3706	3566	3485	3425	3211	3040	2768	2525	2159	1948	1689	1120	716	458
6000	1500	3753	3609	3503	3299	2929	2681	2466	2259	1886	1618	1179	587	447	407
6000	2000	3874	3739	3515	3153	2688	2409	2209	2013	1664	1358	625	303	295	250
7000	100	3052	2990	2910	2746	2255	1939	1846	1763	1607	1479	1312	975	864	843
7000	500	3470	3393	3386	3356	3243	2926	2669	2460	2223	1977	1799	1480	1261	905
7000	1000	3497	3305	3194	3138	3031	2890	2549	2218	1908	1728	1618	1011	639	419
7000	1500	3564	3355	3194	2933	2664	2452	2208	1987	1689	1438	985	459	278	156
7000	2000	3694	3501	3240	2823	2437	2157	1942	1780	1557	1153	481	246	184	112

3.2. *Analysis.* Due to the reliability of the LUT approach, it is widely used to predict CHF of horizontal flow, CHF_{hor} , in many industries including nuclear power generation for which accuracy of prediction is crucial. To use the CHF-LUT to predict CHF occurrence in horizontal tube, the LUT values are adjusted to account for flow stratification. Groeneveld [11]

suggested that the CHF for vertical flow, CHF_{ver} , be multiplied by a stratification factor K_{strat} such that

$$\text{CHF}_{\text{hor}} = K_{\text{strat}} \cdot \text{CHF}_{\text{ver}} \quad (4)$$

To determine the stratification factor, the exact flow regime must be known. Figure 5 shows the flow-regime map

FIGURE 1: Effect of pressure on CHF for vertical up-flow of water in 67 mm diameter tube as predicted by CHF-LUT.

TABLE 2: Effect of high heat flux and tube blockage on CHF occurrence for a 67 mm vertical boiler tube.

Parameter	Base case	High heat flux case	90% tube blockage
Heat flux (KW·m ⁻²)	100	400	100
Pressure (kPa)	6,000	6,000	6,000
Vertical heated length (m)	10	10	10
Inlet quality to vertical tube (—)	0	0	0
Mass flux (kg·m ⁻² ·s ⁻¹)	1,000	1,000	100
Tube exit quality (—)	0.038	0.152	0.380
Critical heat flux (kW·m ⁻²)	3,262	2,760	1,580

for horizontal flow (modified from Taitel and Dukler [12] by [13]). The modification included the extension of curve D into the annular flow regime (Lockhart-Martinelli's parameter, $X_{LM} < 1.6$), resulting in subdivision of the annular regime into homogeneous annular and stratified annular.

For stratified-flow regimes, the liquid waves will not be sufficiently large to cool the upper part of the tube which leads to a CHF value and K_{strat} of zero. If the flow regime falls in the homogeneous annular region (above the line DD'), the effect of orientation on the phase distribution is insignificant. The CHF for horizontal flow may be assumed equal to that for vertical flow and $K_{strat} = 1.0$. For flow conditions between curves A and D, the stratification factor

K_{strat} varies from zero to unity. As a quick estimate, a linear interpolation was used to evaluate K_{strat} [14]. However, Wong [13] showed that a large portion of the horizontal CHF data was underpredicted using direct interpolation. A more accurate prediction method for K_{strat} was developed by Wong [13]. A dimensionless parameter, T_1 , representing the ratio of turbulence to gravity force was derived as follows:

$$T_1 = 0.046 \text{Re}_L^{-0.2} \left(\frac{1-x}{1-\alpha} \right)^2 \frac{G^2}{g D_{hy} \rho_f (\rho_f - \rho_g) \alpha^{0.5}}, \quad (5)$$

where Re_L is liquid Reynolds number, g is gravitational acceleration, α is void fraction, and ρ is density. The subscripts f and g denote saturated liquid and vapor, respectively.

FIGURE 5: Modified, generalized, flow-regime map for horizontal flow [13].

FIGURE 6: Effect of pressure on CHF for horizontal flow of water in 67 mm diameter tube as predicted by CHF-LUT.

Therefore, using the table look-up technique, the CHF in a horizontal tube is calculated with

$$\text{CHF}_{\text{hor}} = C_1 K_{\text{strat}} \text{CHF}_{\text{ver}} \quad (8)$$

3.3. Discussion. At the same flow conditions for a horizontal tube and vertical tube, it is more likely for CHF to occur in

the horizontal tube first. The main reasons which led to this argument are:

- (i) flow stratification may cause partial dryout at low mass fluxes and high qualities;
- (ii) the presence of the partial dryout causes a reduction in the CHF value;

FIGURE 7: Effect of mass flux on CHF for horizontal flow of water in 67 mm diameter tube as predicted by CHF-LUT.

FIGURE 8: Safety limits of the operation of boiler for 50% allowable heat flux.

- (iii) in addition, corrosion potential is higher due to the change in flow direction and due to partial/complete dryout.

So, more detailed examination is performed on the horizontal flow configuration.

The vertical CHF-LUT was used with (6) and (7) to build a LUT for CHF in horizontal flow. The resulting LUT is shown in Table 3 for the same conditions of the vertical tube table. It is clear in the table that the CHF values are much less for the horizontal flow than those of the vertical flow for the same pressures, mass fluxes, and qualities.

Figure 6 shows the effect of pressure on CHF for different mass fluxes. In all cases, the CHF value decreases with increasing pressure. In Figure 6(a) one can expect that flow stratification is high which results in low values of CHF for the whole range of qualities. At higher mass fluxes (Figures 6(b) and 6(c)), the pressure effect is weakened at quality of about 0.4 followed by sudden drop in CHF values. This drop in CHF results from the high quality which leads to stronger effect of flow stratification.

The effect of mass flux on CHF is shown in Figure 7. For qualities less than 0.4 the CHF value increases with increasing mass flux. At higher qualities, the sudden drop in CHF leads to a reverse effect of mass flux.

Similar to the vertical flow analysis, some cases of boiler operation conditions are investigated and the results are shown in Table 4. The results show that for the base case (normal operation conditions) the CHF value is seven times higher than the operating heat flux. So for this case, any failure of the boiler tube may result due to other causes than dryout (e.g., corrosion). Although at this CHF value, it is still safe to operate the boiler, the safety margin is much less than that of a vertical flow.

The second case of Table 4 is for high heat flux. In this case, the CHF value is not much higher than the operating heat flux, and CHF could happen for this case. Also for the case of 80% tube blockage, CHF is very close to the operating heat flux. At 90% tube blockage the whole flow is affected by flow stratification, and the CHF is lower than the operating heat flux. This is likely to lead to complete dryout of the boiler

TABLE 3: CHF-LUT for horizontal flow in 67 mm diameter tube.

P (kPa)	G (kg·m ⁻² ·s ⁻¹)	Quality, x (—)													
		−0.15	−0.10	−0.05	0.00	0.05	0.10	0.15	0.20	0.30	0.40	0.50	0.60	0.70	0.80
		Critical heat flux, CHF (kW·m ⁻²)													
100	100	63	50	35	26	41	52	61	67	76	83	88	87	72	56
100	500	650	532	465	399	369	405	447	478	478	467	441	358	227	168
100	1000	1347	1157	1107	960	729	678	687	666	611	499	491	432	256	129
100	1500	1596	1426	1270	1086	799	731	725	691	628	560	559	481	253	105
100	2000	1637	1428	1271	1090	811	749	737	703	619	578	547	442	203	55
1000	100	68	64	58	51	72	78	85	90	92	89	77	61	59	55
1000	500	508	497	370	586	748	739	731	727	680	440	341	225	188	183
1000	1000	795	778	1039	1272	1372	1266	1197	1160	871	568	437	281	178	136
1000	1500	1152	1128	1517	1673	1687	1483	1390	1279	975	469	280	192	124	111
1000	2000	1566	1533	1625	1809	1828	1566	1422	1327	947	414	215	163	103	41
2000	100	70	66	62	56	69	73	80	85	89	86	79	68	62	51
2000	500	583	576	404	526	654	693	689	675	645	462	432	346	255	209
2000	1000	897	895	957	1178	1270	1230	1181	1135	898	650	550	397	260	186
2000	1500	1217	1187	1340	1522	1582	1486	1401	1246	982	640	400	259	156	131
2000	2000	1641	1611	1648	1705	1700	1584	1512	1342	999	550	290	173	108	70
3000	100	71	69	66	63	72	76	83	88	92	90	85	79	69	53
3000	500	622	620	426	515	632	697	707	682	660	510	534	465	326	244
3000	1000	908	900	937	1109	1227	1234	1200	1151	943	737	659	505	337	232
3000	1500	1275	1260	1341	1473	1536	1504	1426	1251	1010	771	502	318	186	149
3000	2000	1708	1689	1695	1727	1700	1637	1534	1323	1050	687	365	183	112	99
4000	100	70	68	65	64	68	71	78	83	87	86	80	75	67	52
4000	500	623	619	412	456	538	578	591	596	591	508	504	450	349	261
4000	1000	868	841	845	939	1016	1028	1014	996	872	732	677	496	346	250
4000	1500	1266	1246	1247	1289	1272	1244	1204	1114	939	770	541	326	225	207
4000	2000	1694	1664	1613	1575	1477	1410	1340	1213	1008	729	383	192	154	148
5000	100	69	67	65	66	64	66	73	77	81	81	75	71	65	50
5000	500	622	614	396	400	451	470	485	517	524	499	472	431	364	271
5000	1000	828	784	758	783	826	841	844	851	802	721	688	486	353	266
5000	1500	1255	1228	1156	1116	1032	1009	1001	985	870	766	575	334	262	265
5000	2000	1678	1636	1530	1425	1264	1196	1159	1107	966	770	401	201	196	196
6000	100	76	74	72	67	61	63	68	72	75	75	70	54	47	41
6000	500	517	503	378	366	410	422	437	457	469	454	444	388	334	239
6000	1000	796	737	705	711	725	753	738	722	694	683	634	445	299	200
6000	1500	1206	1166	1093	1023	928	885	858	827	763	704	542	281	222	208
6000	2000	1691	1587	1471	1315	1145	1057	1008	964	863	718	330	160	156	132
7000	100	81	79	77	67	58	58	62	65	68	68	63	48	42	38
7000	500	422	405	365	339	379	387	389	387	398	391	382	332	295	220
7000	1000	771	701	663	650	649	678	644	600	582	577	581	385	257	177
7000	1500	1174	1116	1026	927	853	802	745	696	656	604	439	215	135	79
7000	2000	1702	1525	1394	1200	1049	945	877	837	792	610	254	130	97	59

tubes causing either failure of the tubes or accelerating the corrosion.

To determine the safety limits of the boiler, an allowable heat flux was taken to be 50% of the corresponding CHF. Figure 8 shows the safety operational limits at different pressure. As the CHF is expected to occur downstream of the flow, corresponding exit qualities are shown on the same figure.

The boiler will operate safely as long as the operation conditions are to the left of the heat flux line and the mass flux is above the intersection of the exit quality line and the heat flux line. For example, at a pressure of 6000 kPa and a heat flux of 300 kW·m⁻², the mass flux should not be below 800 kg·m⁻²·s⁻¹ and the quality should be to the left of the 300 kW·m⁻² curve.

TABLE 4: Effect of high heat flux and tube blockage on CHF occurrence.

Parameter	Base case	High heat flux case	80% tube blockage	90% tube blockage
Heat flux ($\text{kW}\cdot\text{m}^{-2}$)	100	400	100	100
Pressure (kPa)	6,000	6,000	6,000	6,000
Heated length (m)	15	15	15	15
Inlet quality to vertical tube (—)	0	0	0	0
Mass flux ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	1,000	1,000	200	100
Tube exit quality (—)	0.057	0.228	0.285	0.570
Critical heat flux ($\text{kW}\cdot\text{m}^{-2}$)	729	714	173	58.8

4. Procedures of Determining Safety Limits Using the LUT Approach

The LUT can easily be used to determine the safety limits of boiler operations by applying the following steps.

- (1) Determine the operating pressure (P).
- (2) Estimate the mass flux (G) in each boiler tube and determine the minimum value. If not possible, determine the average mass flux as

$$G_{\text{avg}} = \frac{\dot{m}}{A_{c,\text{total}}}. \quad (9)$$

- (3) Calculate the thermodynamic equilibrium quality (x). The CHF occurrence is expected at higher qualities which means downstream of the flow. The quality at any location along the boiling length can be obtained using the heat balance equation such that

$$x(L) = x_{\text{in}} + \frac{4q_{\text{operate}}}{DGH_{fg}}, \quad (10)$$

where x_{in} is the inlet quality, q is the heat flux, and H_{fg} is the latent heat of vaporization.

- (4) Use the tube diameter modified CHF-LUT to evaluate $q_{\text{CHF}} = f(P, G, x)$. Interpolation between the values for nongrid points might be necessary.
- (5) Compare the operating heat flux to the calculated CHF value (considering q_{CHF} uncertainty).

If $q_{\text{operate}} < q_{\text{CHF}}$, then the boiler is operated safely and CHF is unlikely to occur.

If $q_{\text{operate}} > q_{\text{CHF}}$, then the boiler operation exceeds safety limits and accidents may occur.

The CHF-LUT can easily be programmed into a computer code for quick interpolation and other calculations.

5. Other Considerations

The CHF-LUTs for this work are developed for steady-state water flow in uniformly heated tubes with inside diameter of 67 mm. During normal operation of reactors, boilers, and steam generators, the heat flux is nonuniform. Also the flow

fluctuates in pressure and mass flux. For such cases, the CHF-LUTs still can be used with some considerations.

Most CHF measurements have been obtained in uniformly heated tubes because of relative ease in construction of the test section and known location of dryout (downstream end of heated length). Hence, the large majority of CHF prediction methods were derived based only on the data of uniformly heated channels. A change in axial-flux distribution (AFD) from uniform to nonuniform can have an effect on the location of dryout and magnitude of CHF or dryout power since:

- (i) the location of dryout may shift from the downstream end to well upstream from the downstream end (the shift in initial-dryout location depends primarily on the shape of AFD and flow conditions), and
- (ii) the location of dryout and magnitude of CHF is affected by upstream history of the flow (flow memory effect).

Yang et al. [15] performed experimental study on the effect of AFD on CHF. They concluded that the AFD effect on CHF power is relatively small. The CHF power increases slightly as a result of AFD change from uniform to nonuniform in addition to the shifting in CHF location at low inlet qualities. This slight increase in CHF, especially at low inlet temperature, makes it more conservative to apply the CHF-LUT.

El Nakla [16] showed that the steady-state CHF prediction techniques can be used to predict flow oscillation and flow transients CHF with great accuracy. The method used in such cases is applying the instantaneous local conditions of the flow. For instance, if the flow is oscillating, then it is only needed to determine the flow conditions (P , G , and X) at a specific instant, and by using these values along the CHF-LUT, the safety limits can be determined as in steady-state cases.

Corrosion of tubes might play a major role in boiler tube failure especially after a sudden turn and in horizontal flow where flow stratification could result in dryout or partial dryout in the tube. Collier and Thome [10] provided that the corrosion in such flow configurations is very quick, and they also summarized some of the previous work on the topic.

6. Conclusions

Two look-up tables were developed to predict critical heat flux in vertical and horizontal boilers tubes. The tables are

applicable for 67 mm diameter tubes with water as coolant. These tables cover wide range of flow conditions ($P = 100\text{--}7000$ kPa, $G = 100\text{--}2000$ kg·m⁻²·s⁻¹, and $x = -0.15\text{--}0.80$) so that they can be used during normal operation as well as during accident scenarios and flow oscillation.

The derived CHF-LUTs show correct asymptotic trends compared to those reported in the literature. The prediction accuracy for the vertical LUT is expected to be better than that of the horizontal one. This is due to the less imposed correction on the vertical flow table and the general practice in applying the table for vertical flow. The results of the analysis showed that the vertical flow will unlikely experience any dryout while the chances are much higher for dryout in the horizontal part.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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