ANL-75-55

THERMOPHYSICAL PROPERTIES OF STAINLESS STEELS

by

Choong S. Kim

BASE TECHNOLOGY

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ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

Prepared for the U.S. ENERGY RESEARCH
AND DEVELOPMENT ADMINISTRATION
Division of Reactor Research and Development
under Contract W-31-109-Eng-38

Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price: Printed Copy $4.00; Microfiche $2.25

Distribution Category:
LMFBR Fuels and Materials
Engineering and Development
(UC-79b)

ANL-75-55

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Chemical Engineering Division

September 1975

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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ABSTRACT

Recommended values of the thermodynamic and transport properties of stainless steels Type 304L and Type 316L are given for temperatures from 300 to 3000 K. The properties in the solid region were obtained by extrapolating available experimental data to the melting range, while appropriate correlations were used to estimate these properties in the liquid region. The properties evaluated include the enthalpy, entropy, specific heat, vapor pressure, density, thermal expansion coefficient, thermal conductivity, thermal diffusivity, and viscosity.

I. INTRODUCTION

Analyses of hypothetical core disruptive accidents (HCDA) in nuclear reactors require the knowledge of selected thermophysical properties of stainless steels at high temperatures. Since there are no experimental data for the thermodynamic and transport properties of stainless steels at the high temperatures of interest, data at these high temperatures have to be obtained by estimation or by extrapolation of data at lower temperatures. It is the objective of this report to estimate selected properties at the high temperatures of interest to reactor analysts.

Various types of stainless steels are used in nuclear reactors as fuel cladding and structural materials because of their favorable nuclear characteristics, corrosion resistance, and good mechanical properties. Stainless steels Type 304L and Type 316L are two such materials and are the subject of present study. Table 1 shows the approximate compositions of these materials.

TABLE 1. Compositions of Stainless Steels Type 304L and Type 316L (weight per cent)

Type	Carbon (maximum)	Chromium	Nickel	Molybdenum	Iron
304L	0.03	18.0 - 20.0	8.0 - 11.0	-	remainder
316L	0.03	16.0 - 18.0	10.0 - 14.0	1.75 - 2.5	remainder

Thermophysical properties of stainless steels Type 304L and Type 316L evaluated for temperatures from 300 K to 3000 K are presented below. These properties include enthalpy, entropy, specific heat, vapor pressure, density, thermal expansion coefficient, thermal conductivity, thermal diffusivity, and viscosity. This information is essential in heat- and mass-transfer analyses related with HCDA's.

II. CALCULATION PROCEDURES AND RESULTS

A. Enthalpy, Entropy, and Specific Heat

Experimental data[1,2] exist for the enthalpy and specific heat of stainless steels Type 304L and Type 316 for temperatures up to 1620 and 1170 K, respectively. These sets of experimental values were smoothed by us, using least-square techniques, and extrapolated to the melting range (1670-1730K).

The only difference in composition between Type 316 and 316L stainless steels is the maximum carbon content; 0.10% for Type 316 and 0.03% for Type 316L. Accordingly, there is a negligible difference in enthalpy between the two stainless steels. Therefore, the enthalpy values thus evaluated are recommended for stainless steels Types 304 and 304L and Types 316 and 316L in the solid region. These values are represented by the following functional equations:

Type 304L:

$$H_T^\circ - H_{298.15}^\circ = -34.885 + 0.1122\ T + 1.611\times10^{-5}\ T^2 \qquad (1)$$

Type 316L:

$$H_T^\circ - H_{298.15}^\circ = -34.127 + 0.1097\ T + 1.587\times10^{-5}\ T^2 \qquad (2)$$

where $H_T^\circ - H_{298.15}^\circ$ = enthalpy in cal/g and T = temperature in K.

Specific heat and entropy values in the solid region were obtained for these steels by applying the following thermodynamic relationships to the enthalpy data:

$$c_p^\circ = \frac{d}{dT}\left(H_T^\circ - H_{298.15}^\circ\right) \qquad (3)$$

$$s_T^\circ - s_{298.15}^\circ = \int_{298.15}^{T} \frac{d\left(H_T^\circ - H_{298.15}^\circ\right)}{T} = \int_{298.15}^{T} \frac{c_p^\circ\, dT}{T} \qquad (4)$$

The values thus derived are given by the functional equations as follows:

Type 304L:

$$c_p^\circ = 0.1122 + 3.222\times10^{-5}\ T \tag{5}$$

$$s_T^\circ - s_{298.15}^\circ = 0.1122\ \ln T + 3.222\times10^{-5}\ T - 0.6489 \tag{6}$$

Type 316L:

$$c_p^\circ = 0.1097 + 3.174\times10^{-5}\ T \tag{7}$$

$$s_T^\circ - s_{298.15}^\circ = 0.1097\ \ln T + 3.174\times10^{-5}\ T - 0.6345 \tag{8}$$

where c_p° = specific heat in cal/(g)(K), $s_T^\circ - s_{298.15}^\circ$ = entropy in cal/(g)(K), and T = temperature in K.

Although thermodynamic data for stainless steels are not available in the liquid region, data[3] exist for the major constituent elements such as iron, chromium, nickel, and molybdenum at high temperatures. The values in Ref. 3 had been selected from several sets of experimental data which are available for the temperatures up to about 1900, 2000, 2200, and 3000 K for Fe, Cr, Ni, and Mo, respectively, and extrapolated to their boiling points. Douglas[4] found that the specific heats of solutions of liquid metals are roughly additive and this approximation is good especially when the properties of the components are similar. It was also reported[5] that the liquid Fe-Cr-Ni alloys behave essentially ideally.

On the basis of the above information, specific heats of stainless steels in the liquid region were estimated by the additivity rule. In this estimation, stainless steel Type 304L was considered to be composed of 72% Fe, 19% Cr, and 9% Ni; and Type 316L, of 69% Fe, 17% Cr, 12% Ni, and 2% Mo, by weight. Specific heat data for the constituent elements were provided by Ref. 3. Averaged values, 0.190 and 0.184 cal/(g)(K), were taken as the specific heats of Type 304L and Type 316L stainless steels, respectively, in the liquid region. Taking constant specific heat values was based on the fact that the temperature dependency of specific heats is very small for most liquid metals.

Enthalpies and entropies were then calculated from the specific heat data by using appropriate thermodynamic relations. In doing so, a value of 64.0 cal/g was used for the heat of fusion for both Type 304L and Type 316L stainless steels. This value was obtained by applying the additivity rule to the existing data[3] for the heats of fusion of the constituent elements. Heats of vaporization of the two stainless steels were calculated in a similar way, and a value of 1770 cal/g was obtained for both types of stainless steels. The entropy change due to melting was obtained by dividing the heat of fusion by the melting temperature, 1700 K. A value of 0.0377 cal/(g)(K) was obtained for both types of stainless steels. This

corresponds roughly to R [2 cal/(mol)(K)] which is reasonable. Enthalpy and entropy values of stainless steels in the liquid region are represented by the following equations:

Type 304L:

$$H^{\circ}_{T}-H^{\circ}_{298.15} = 0.1900\ T - 56.588 \quad (9)$$

$$s^{\circ}_{T}-s^{\circ}_{298.15} = 0.1900\ \ln T - 1.1351 \quad (10)$$

Type 316L:

$$H^{\circ}_{T}-H^{\circ}_{298.15} = 0.1840\ T - 50.573 \quad (11)$$

$$s^{\circ}_{T}-s^{\circ}_{298.15} = 0.1840\ \ln T - 1.0955 \quad (12)$$

where $H^{\circ}_{T}-H^{\circ}_{298.15}$ = enthalpy in cal/g, $s^{\circ}_{T}-s^{\circ}_{298.15}$ = entropy in cal/(g)(K) and T = temperature in K.

Recommended values of thermodynamic properties of stainless steels Type 304L and Type 316L are given for temperatures 300 to 3000 K in Table 2 and Figs. 1 through 3. These sets of values are also recommended for stainless steels Type 304 and Type 316, respectively.

B. Vapor Pressure

Experimental data are not available for the vapor pressure of stainless steels at the high temperatures of interest to reactor safety analysts. However, a mass-spectrometric study[5] of activities in Fe-Cr-Ni alloys supports an ideal-solution treatment of stainless steels at high temperatures. Vapor pressures of stainless steels were calculated according to this simple solution model, treating Type 304L stainless steel as composed of 0.713, 0.202, and 0.085 atom fractions of Fe, Cr, and Ni, respectively, and Type 316L stainless steel, of 0.691, 0.183, 0.114, and 0.012 atom fractions of Fe, Cr, Ni, and Mo, respectively. In this report, the vapor-pressure data for the major constituent elements were taken from Ref. 3. These values are given in Table 3.

Vapor pressure values estimated by the additivity rule were smoothed by fitting into functions of log(vapor pressure) *vs.* 1/(T,K). Functional relationships between vapor pressure and temperature above melting points are given by the following equations:

Type 304L:

$$\log P = 6.1210 - \frac{18836}{T} \quad (13)$$

TABLE 2. Thermodynamic Properties of Stainless Steels Type 304L and Type 316L

	Type 304L			Type 316L		
Temp., K	Sp. Heat, cal/(g)(K)	Enthalpy, cal/g	Entropy, cal/(g)(K)	Sp. Heat, cal/(g)(K)	Enthalpy, cal/g	Entropy, cal/(g)(K)
300	0.1219	0.23	0.0007	0.1192	0.21	0.0007
400	0.1251	12.57	0.0362	0.1224	12.29	0.0355
500	0.1283	25.24	0.0645	0.1256	24.69	0.0631
600	0.1315	38.24	0.0882	0.1287	37.41	0.0863
700	0.1348	51.55	0.1087	0.1319	50.44	0.1064
800	0.1380	65.19	0.1269	0.1351	63.79	0.1242
900	0.1412	79.14	0.1433	0.1383	77.46	0.1403
1000	0.1444	93.43	0.1584	0.1414	91.44	0.1550
1100	0.1476	108.03	0.1723	0.1446	105.75	0.1687
1200	0.1509	122.95	0.1853	0.1478	120.37	0.1814
1300	0.1541	138.20	0.1975	0.1510	135.30	0.1933
1400	0.1573	153.77	0.2090	0.1541	150.56	0.2046
1500	0.1605	169.66	0.2200	0.1573	166.13	0.2154
1600	0.1638	185.88	0.2304	0.1605	182.02	0.2256
1700(s)	0.1670	202.41	0.2405	0.1637	198.23	0.2355
1700(ℓ)	0.1900	226.41	0.2782	0.1840	262.23	0.2732
1800	0.1900	285.41	0.2891	0.1840	280.63	0.2837
1900	0.1900	304.41	0.2993	0.1840	299.03	0.2936
2000	0.1900	323.41	0.3091	0.1840	317.43	0.3031
2100	0.1900	342.41	0.3183	0.1840	335.83	0.3120
2200	0.1900	361.41	0.3272	0.1840	354.23	0.3206
2300	0.1900	380.41	0.3356	0.1840	372.63	0.3288
2400	0.1900	399.41	0.3437	0.1840	391.03	0.3366
2500	0.1900	418.41	0.3515	0.1840	409.43	0.3441
2600	0.1900	437.41	0.3589	0.1840	427.83	0.3513
2700	0.1900	456.41	0.3661	0.1840	446.23	0.3583
2800	0.1900	475.41	0.3730	0.1840	464.63	0.3650
2900	0.1900	494.31	0.3797	0.1840	483.03	0.3714
3000	0.1900	513.41	0.3861	0.1840	501.43	0.3777

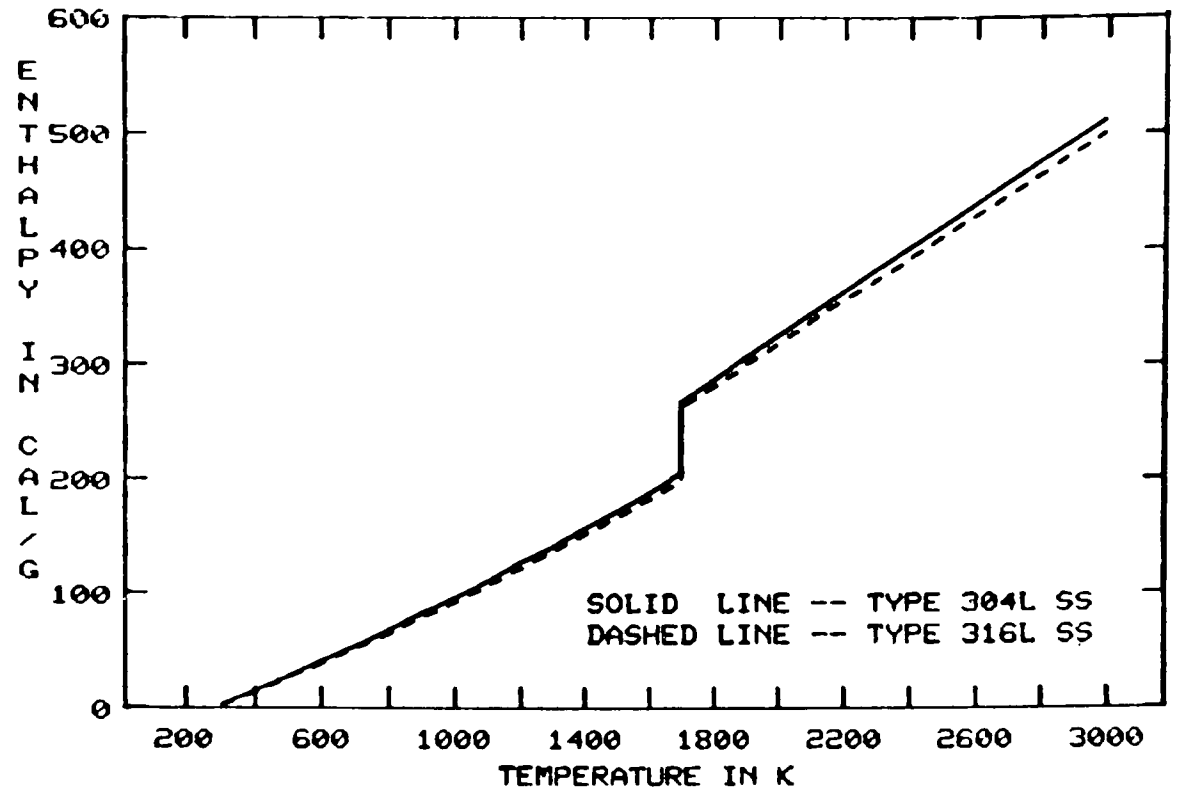

Fig. 1. Enthalpies of Stainless Steels *vs.* Temperature.

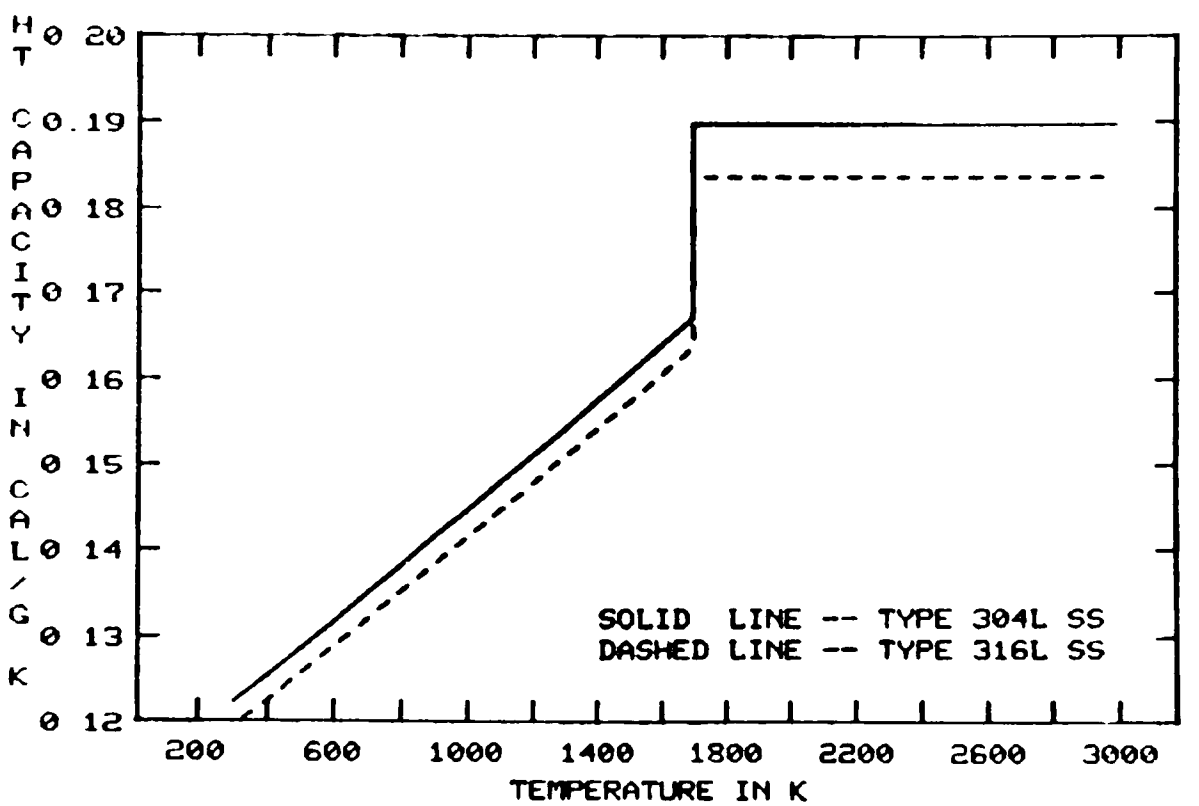

Fig. 2. Specific Heats of Stainless Steels *v*

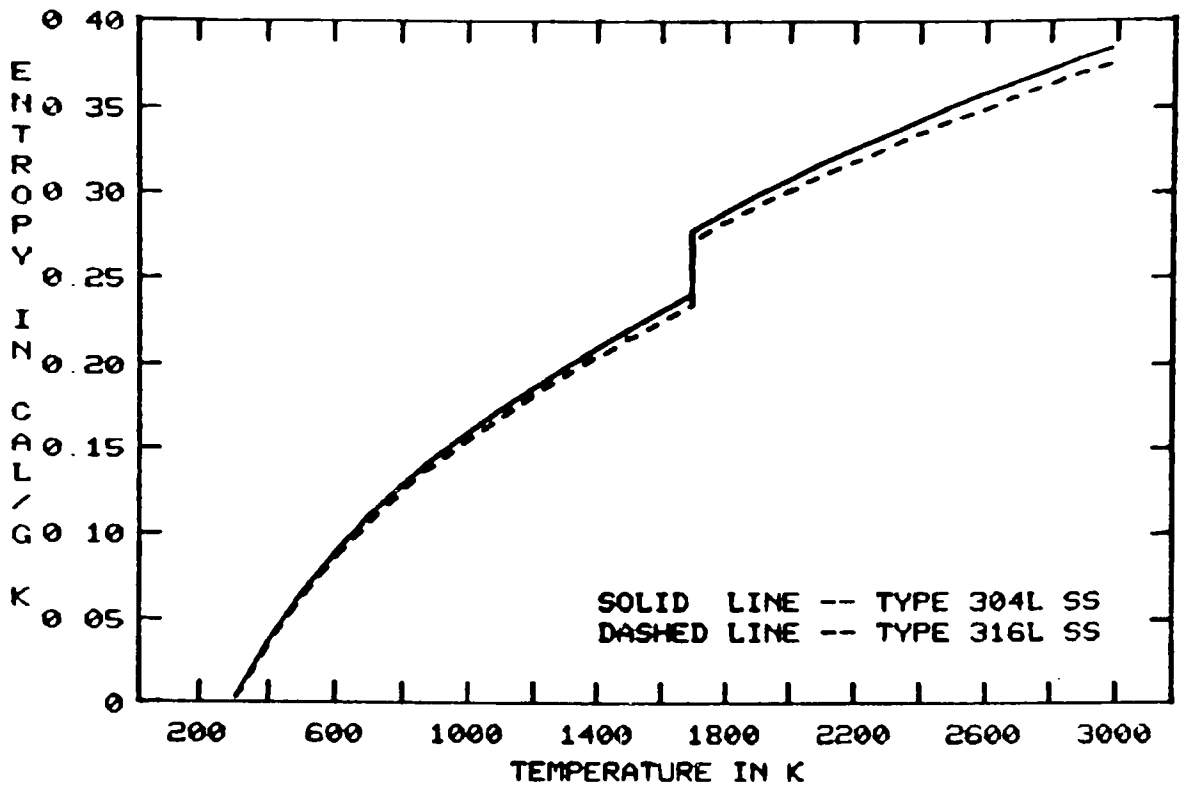

Fig. 3. Entropies of Stainless Steels *vs.* Temperature.

Type 316L:

$$\log P = 6.1127 - \frac{18868}{T} \qquad (14)$$

where P is vapor pressure in atm and T is temperature in K.

Boiling points of stainless steels were readily calculated from the above equations; they are 3080 and 3090 K for stainless steels Type 304L and Type 316L, respectively. The recommended values of vapor pressure of stainless steels are given in Table 4 and Fig. 4. These values are also recommended for the regular stainless steels because the difference in thermodynamic properties between low carbon and regular stainless steels is negligible, as has been mentioned earlier.

C. Density and Thermal Expansion Coefficient

Experimental data for the density of stainless steels Type 304L or Type 316L do not exist. However, density data[6,7,8] are available for stainless steels Type 304 and Type 316 for the temperatures up to 1600 and 1616 K, respectively. These sets of values were smoothed and extrapolated to the melting range by fitting into polynomials. The values thus obtained are recommended for the densities of stainless steels Type 304L and Type 316L in the solid region, since the effect of carbon contents in stainless steels on the density change may be considered negligible.

TABLE 3. Vapor Pressures of Constituent Elements of Stainless Steels

Temperature (K)	Vapor Pressure (atm)			
	Fe	Cr	Ni	Mo
1700	6.37×10^{-6}	2.00×10^{-5}	2.63×10^{-6}	-
1800	2.99×10^{-5}	8.90×10^{-5}	1.28×10^{-5}	-
1900	(1.13×10^{-4})[a]	3.35×10^{-4}	5.20×10^{-5}	-
2000	(3.70×10^{-4})	1.09×10^{-3}	1.82×10^{-4}	3.1×10^{-10}
2100	-	3.17×10^{-3}	5.60×10^{-4}	-
2200	(2.82×10^{-3})	8.03×10^{-3}	(1.55×10^{-3})	1.02×10^{-8}
2300	-	1.86×10^{-2}	(3.92×10^{-3})	-
2400	(1.50×10^{-2})	3.99×10^{-2}	(9.11×10^{-3})	1.87×10^{-7}
2500	-	(8.03×10^{-2})	(1.97×10^{-2})	-
2600	(6.07×10^{-2})	(0.154)	(4.00×10^{-2})	2.16×10^{-6}
2700	-	(0.278)	(7.70×10^{-2})	-
2800	(0.198)	(0.482)	(0.141)	1.73×10^{-5}
2900	-	(0.804)	(0.246)	-
3000	(0.546)	(1.30)	(0.414)	9.88×10^{-5}
3100	-	-	-	-
3200	(1.31)	-	(1.06)	(4.34×10^{-4})

[a]Values enclosed by parentheses are extrapolated values.

Hull[9] derived a formula by which the densities of alloys can be calculated from their compositions and the density values of their constituent elements:

$$\rho = 1/\sum_i (x_i/\rho_i) \tag{15}$$

where ρ is the density of the alloy, ρ_i and x_i are the density and weight fraction of the i^{th} constituent element, respectively. There exist the

TABLE 4. Vapor Pressures of Stainless Steels Type 304L and Type 316L

Temp. (K)	Vapor Pressure (atm) Type 304L	Type 316L
1700	1.099×10^{-5}	1.032×10^{-5}
1800	4.535×10^{-5}	4.270×10^{-5}
1900	1.612×10^{-4}	1.521×10^{-4}
2000	5.047×10^{-4}	4.772×10^{-4}
2100	1.417×10^{-3}	1.343×10^{-3}
2200	3.624×10^{-3}	3.438×10^{-3}
2300	8.540×10^{-3}	8.114×10^{-3}
2400	1.874×10^{-2}	1.783×10^{-2}
2500	3.860×10^{-2}	3.667×10^{-2}
2600	7.523×10^{-2}	7.174×10^{-2}
2700	1.395×10^{-1}	1.332×10^{-1}
2800	2.477×10^{-1}	2.367×10^{-1}
2900	4.225×10^{-1}	4.041×10^{-1}
3000	6.956×10^{-1}	6.658×10^{-1}
3100	1.109	1.062
3200	1.717	1.646
3300	2.589	2.484
3400	3.811	3.658
3500	5.474	5.270

density data[10,11] for the constituent elements in the liquid region. Reference 10 provides density values of Fe, Cr, and Ni which were selected from several sets of experimental data and extrapolated to 3000 K. The density of Mo can be readily calculated from the thermal expansion data given by Ref. 11. These values are tabulated in Table 5.

Densities of stainless steels Type 304 and Type 316L were estimated according to Eq. (15) from the data for the density of constituent elements, and compared with the experimental data.[6,7] As shown in Table 6, densities thus calculated were found to be within ± 1.6% of the experimental data over the temperature range from 300 to 1600 K. Densities of several alloys, of which experimental data are available in the liquid region, were also calculated by Eq. (15). The comparison between the calculated and experimental values[12] showed a good agreement especially when the densities of constituent

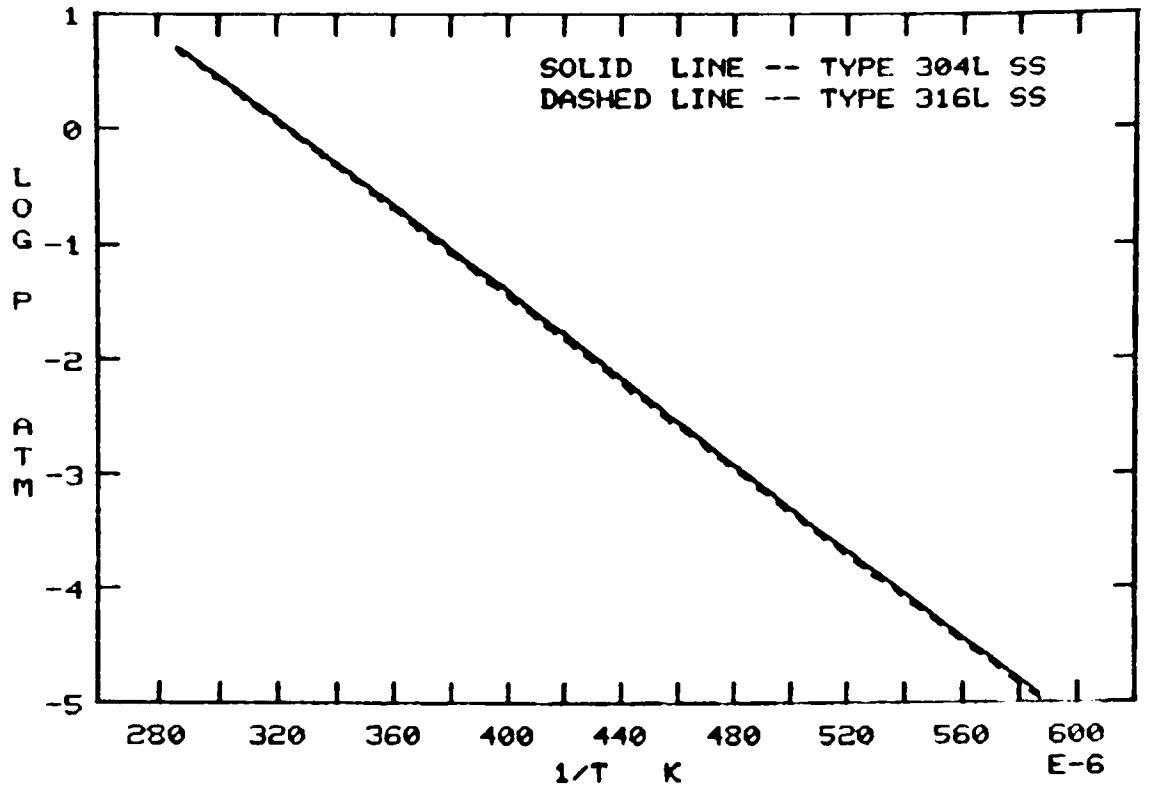

Fig. 4. Vapor Pressures of Stainless Steels *vs.* Temperature.

elements of the alloys are about the same, which is the case for the stainless steels. These two comparisons support the employment of Eq. (15) in the estimation of densities of stainless steels in the liquid region.

Densities of stainless steels Type 304L and Type 316L in the liquid region have been estimated by Eq. (15). In this estimation, stainless steel Type 304L was considered to be composed of 72% Fe, 19% Cr, and 9% Ni; and Type 316L, of 69% Fe, 17% Cr, 12% Ni, and 2% Mo, by weight. Denisty changes due to melting have been calculated similarly; they are 0.279 g/cm^3 and 0.284 g/cm^3, respectively, for Type 304L and Type 316L stainless steels. Density data for the constituent elements were obtained from Refs. 10 and 11.

Functional equations representing the recommended values of density of stainless steels were derived from these values by least-square techniques. These equations are

Type 304L:

$$\rho = 7.9841 - 2.6506\times10^{-4}\ T - 1.1580\times10^{-7}\ T^2 \qquad \text{(solid region)} \qquad (16)$$

$$\rho = 7.5512 - 1.1167\times10^{-4}\ T - 1.5063\times10^{-7}\ T^2 \qquad \text{(liquid region)} \qquad (17)$$

TABLE 5. Densities of Constituent Elements of Stainless Steels

Temperature (K)	Density (g/cm^3)			
	Fe	Cr	Ni	Mo
300	7.865	7.210	8.901	10.240
400	7.838	7.200	8.870	10.220
500	7.808	7.180	8.836	10.210
600	7.715	7.160	8.800	10.190
700	7.739	7.130	8.761	10.180
800	7.700	7.110	8.720	10.160
900	7.658	7.090	8.677	10.140
1000	7.613	7.070	8.631	10.120
1100	7.565	7.040	8.582	10.100
1200	7.589	7.010	8.531	10.080
1300	7.539	6.980	8.477	10.060
1400	7.487	6.940	8.421	10.040
1500	7.433	6.910	8.362	10.020
1600	7.377	6.870	8.301	9.990
1700	7.290	6.830	8.237	9.970
1800	7.260	6.780	7.814	9.950
1900	6.935	6.740	7.696	9.920
2000	6.851	6.690	7.578	9.890
2100	6.768	6.630	7.460	9.870
2200	6.684	6.000	7.342	9.840
2300	6.601	(5.900)[a]	7.224	9.810
2400	6.517	(5.800)	(7.106)	9.780
2500	6.433	(5.700)	(6.988)	9.750
2600	(6.349)	(5.600)	(6.870)	9.710
2700	(6.266)	(5.500)	(6.752)	9.680
2800	(6.182)	(5.400)	(6.634)	9.640
2900	(6.098)	(5.300)	(6.516)	9.610
3000	(6.014)	(5.200)	(6.398)	(9.570)
m. p. (K)	1805	2123	1728	2895
$\Delta\rho_m$[b] (g/cm^3)	0.246	0.50	0.322	-

[a]Values in parentheses were obtained by extrapolating the existing data.

[b]Density change on melting at melting temperature.

TABLE 6. Comparison of Experimental and Calculated Density Values of Type 304 and Type 316 Stainless Steels

	Type 304 SS			Type 316 SS		
Temp (K)	$\rho_{exp.}$[a] (g/cm^3)	$\rho_{calc.}$[b] (g/cm^3)	Deviation[c] (%)	$\rho_{exp.}$[d] (g/cm^3)	$\rho_{calc.}$[b] (g/cm^3)	Deviation[c] (%)
300	7.894	7.812	-1.04	7.954	7.890	-0.81
400	7.860	7.788	-0.92	7.910	7.866	-0.56
500	7.823	7.760	-0.81	7.864	7.838	-0.33
600	7.783	7.687	-1.24	7.818	7.765	-0.68
700	7.742	7.695	-0.61	7.771	7.772	0.01
800	7.698	7.660	-0.49	7.723	7.737	0.18
900	7.652	7.623	-0.38	7.674	7.699	0.33
1000	7.603	7.583	-0.26	7.624	7.659	0.46
1100	7.552	7.539	-0.17	7.574	7.615	0.54
1200	7.499	7.546	0.63	7.523	7.621	1.30
1300	7.444	7.500	0.75	7.471	7.574	1.38
1400	7.386	7.450	0.87	7.419	7.525	1.43
1500	7.326	7.401	1.03	7.365	7.475	1.50
1600	7.264	7.348	1.16	7.311	7.422	1.52

[a] Experimental data from Ref. 6.

[b] Calculated values according to Eq. (15).

[c] $[(\rho_{cal.}-\rho_{exp.})/\rho_{exp.}] \times 100$

[d] Experimental data from Ref. 7.

Type 316L:

$$\rho = 8.0842 - 4.2086\times10^{-4}\ T - 3.8942\times10^{-8}\ T^2 \quad \text{(solid region)} \quad (18)$$

$$\rho = 7.4327 + 3.9338\times10^{-5}\ T - 1.8007\times10^{-7}\ T^2 \quad \text{(liquid region)} \quad (19)$$

where ρ = density in g/cm^3 and T = temperature in K.

Linear thermal expansion coefficients of these steels were calculated from the density values. They are defined as follows:

$$\text{coefficient} = \frac{\text{length at T - length at 298.15 K}}{\text{length at 298.15 K (T-298.15 K)}} \quad (20)$$

for solid region

$$\text{coefficient} = \frac{\text{length at T - length at 1700 K}}{\text{length at 1700 K (T-1700 K)}} \quad (21)$$

for liquid region

These values are represented by the following equations:

Type 304L:

$$B = 1.2632\text{x}10^{-5} + 4.8544\text{x}10^{-9}\ T + 7.2376\text{x}10^{-13}\ T^2 \quad \text{(solid region)} \quad (22)$$

$$B = 2.1678\text{x}10^{-5} + 5.7982\text{x}10^{-10}\ T + 2.5724\text{x}10^{-12}\ T^2 \quad \text{(liquid region)} \quad (23)$$

Type 316L:

$$B = 1.7887\text{x}10^{-5} + 2.3977\text{x}10^{-9}\ T + 3.2692\text{x}10^{-13}\ T^2 \quad \text{(solid region)} \quad (24)$$

$$B = 1.8642\text{x}10^{-5} + 3.9166\text{x}10^{-10}\ T + 2.8327\text{x}10^{-12}\ T^2 \quad \text{(liquid region)} \quad (25)$$

where B = linear expansion coefficient in 1/K and T = temperature in K.

Recommended values of density and linear expansion coefficient of stainless steels Type 304L and Type 316L are given in Table 7 and Figs. 5 and 6.

D. Thermal Conductivity and Thermal Diffusivity

Experimental data[1,13] for the thermal conductivity of stainless steels Type 304L and Type 316 are available for temperatures up to 1600 and 1200 K, respectively. Straight lines were drawn through these sets of data points and extended to the melting range. These sets of values are recommended for the thermal conductivities of stainless steels Type 304L and Type 316L in the solid region, assuming that the effect of carbon content in stainless steels on the thermal conductivity change is negligible.

In the liquid region, no thermal conductivity data are available for steels or their major constituent elements. Therefore, an effort was made to derive general correlations on the thermal conductivity changes due to melting and on the temperature dependency of liquid thermal conductivities from the existing data[14] for several other metal elements.

In Table 8, thermal conductivity values[14] are given for thirteen metals in the solid and liquid states at the melting temperatures. This table shows that, at the melting points, the ratios of thermal conductivities in the solid state to those in the liquid state are about 1.95 for the normal metals (*i.e.*, metals that expand upon melting), excluding Bi and Sb. For comparison, these ratios were calculated for the stainless steels by using the formula derived by Rao[15]:

$$k_s/k_L = \exp\ (80\ \Delta H_f/T_m) \quad (26)$$

TABLE 7. Densities and Linear Expansion Coefficients of Stainless Steels Type 304L and Type 316L

	Type 304L		Type 316L	
Temp (K)	Density (g/cm^3)	Exp. Coeff. $x10^5$ (1/K)	Density (g/cm^3)	Exp. Coeff. $x10^5$ (1/K)
300	7.894	-	7.954	-
400	7.860	1.468	7.910	1.890
500	7.823	1.524	7.864	1.917
600	7.783	1.581	7.818	1.944
700	7.742	1.639	7.771	1.973
800	7.698	1.699	7.723	2.002
900	7.652	1.759	7.674	2.031
1000	7.603	1.821	7.624	2.061
1100	7.552	1.885	7.574	2.092
1200	7.499	1.949	7.523	2.123
1300	7.444	2.016	7.471	2.156
1400	7.386	2.084	7.419	2.188
1500	7.326	2.154	7.365	2.222
1600	7.264	2.225	7.311	2.256
1700(s)	7.199	2.299	7.256	2.291
1700(ℓ)	6.926	-	6.979	-
1800	6.862	3.101	6.920	2.848
1900	6.795	3.207	6.857	2.961
2000	6.725	3.315	6.791	3.078
2100	6.652	3.427	6.721	3.199
2200	6.577	3.543	6.648	3.324
2300	6.498	3.664	6.571	3.455
2400	6.416	3.789	6.490	3.590
2500	6.331	3.919	6.406	3.731
2600	6.243	4.055	6.318	3.878
2700	6.152	4.196	6.226	4.031
2800	6.058	4.344	6.131	4.192
2900	5.961	4.499	6.032	4.360
3000	5.861	4.662	5.930	4.536

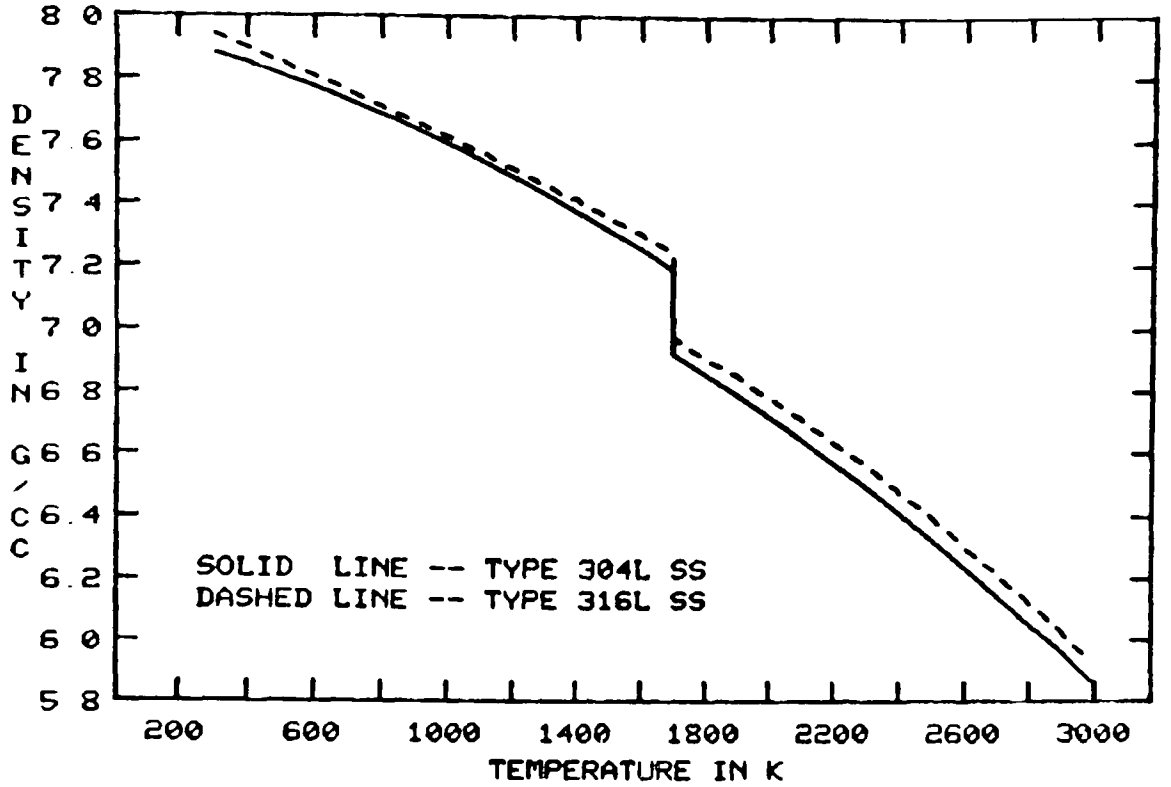

Fig. 5. Densities of Stainless Steels *vs.* Temperature.

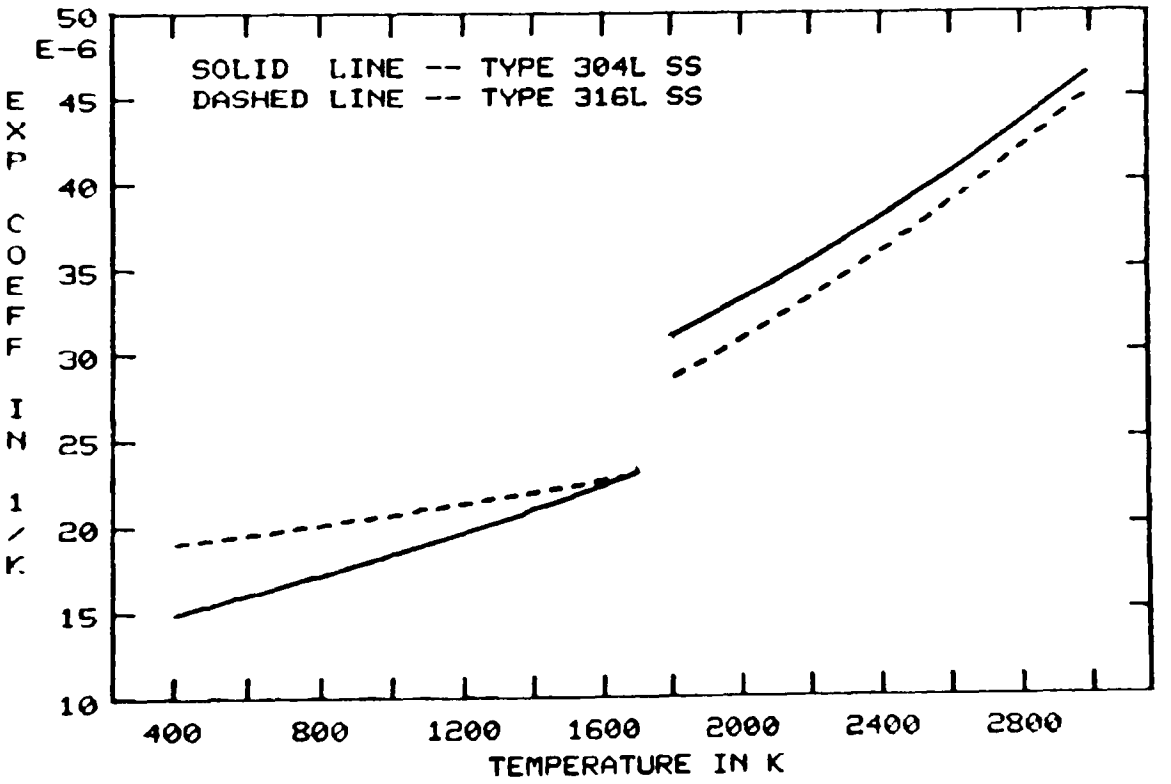

Fig. 6. Linear Thermal Expansion Coefficients of Stainless Steels *vs.* Temperature.

TABLE 8. Thermal Conductivity Changes on Melting of Metal Elements

Metal	T_m, Melting Temperature (K)	k_s, Thermal Conductivity in Solid State (W cm^{-1} K^{-1})	k_l, Thermal Conductivity in Liquid State (W cm^{-1} K^{-1})	k_s/k_l
Al	933.5	2.08	0.907	2.293
Bi	544.6	0.065	0.124	0.524
Cd	594.3	0.880	0.368	2.391
Cs	301.9	0.359	0.197	1.822
Cu	1357.6	3.28	1.66	1.976
In	429.8	0.729	0.382	1.908
K	336.8	0.985	0.548	1.748
Li	453.7	0.772	0.428	1.804
Na	371.0	1.32	0.883	1.495
Pb	600.7	0.314	0.155	2.026
Sb	903.9	0.167	0.259	0.645
Sn	505.1	0.595	0.303	1.964
Zn	692.7	0.993	0.495	2.006

where k_s and k_L are thermal conductivities in solid and liquid states, respectively; ΔH_f is the heat of fusion in kilo-joules/g mole; and T_m is the melting temperature in K. The ratios thus derived were 2.01 and 2.03 for stainless steels Type 304L and Type 316L, respectively.

Experimental thermal conductivity data for eight molten metals* from Ref. 14 were tabulated in Table 9. In this table, T_m and k_m represent melting temperature and thermal conductivity in the liquid state at the melting temperature, respectively. These values show that the thermal conductivities of these molten metals increase linearly with temperature, with a slope that is nearly the same for all these elements over small temperature ranges** above the melting points. The data for the eight metals were fitted to the following equation:

$$k/k_m - 1 = C\ (T/T_m - 1) \tag{27}$$

In the above equation, k and k_m denote thermal conductivities of molten metal at the temperature T and at the melting temperature, respectively. T and T_m

*Al, Cd, Cs, Cu, Zn, Li, Pb, and Sn

**Temperatures up to 1.33 times the melting temperature for Pb, 2.09 times the melting temperature for In, and in between for the other elements.

TABLE 9. Experimental and Calculated Values of Liquid Metal Thermal Conductivities

Metal	T, temp. (K)	k, Therm. Conductivity ($W\ cm^{-1}\ K^{-1}$)	T/T_m	k/k_m	$(k/k_m)^a$	Error (%)
Al	933.5	0.907	1.000	1.000	-	-
	1000.0	0.930	1.071	1.025	1.022	-0.29
	1100.0	0.964	1.178	1.063	1.055	-0.74
	1200.0	0.994	1.285	1.096	1.088	-0.70
	1273.2	1.020	1.364	1.125	1.113	-1.08
Cd	594.3	0.368	1.000	1.000	-	-
	700.0	0.396	1.178	1.076	1.055	-1.93
	800.0	0.420	1.346	1.141	1.107	-2.96
	900.0	0.439	1.514	1.193	1.159	-2.82
Cs	301.9	0.197	1.000	1.000	-	-
	400.0	0.203	1.325	1.030	1.101	6.87
	500.0	0.205	1.656	1.041	1.203	15.60
Cu	1357.6	1.66	1.000	1.000	-	-
	1400.0	1.67	1.031	1.006	1.010	0.36
	1500.0	1.71	1.105	1.030	1.033	0.25
	1600.0	1.74	1.179	1.048	1.055	0.71
	1700.0	1.77	1.252	1.066	1.078	1.14
	1800.0	1.79	1.326	1.078	1.101	2.14
	1900.0	1.81	1.400	1.090	1.124	3.12
In	429.8	0.382	1.000	1.000	-	-
	500.0	0.394	1.163	1.031	1.051	1.89
	600.0	0.425	1.395	1.113	1.122	0.85
	700.0	0.453	1.628	1.186	1.195	0.73
	800.0	0.479	1.860	1.254	1.267	1.00
	900.0	0.494	2.093	1.293	1.339	3.54
Li	453.7	0.428	1.000	1.000	-	-
	500.0	0.443	1.102	1.035	1.032	-0.29
	600.0	0.476	1.322	1.112	1.100	-1.10
	700.0	0.509	1.543	1.189	1.168	-1.74
	800.0	0.541	1.763	1.264	1.237	-2.17
	900.0	0.572	1.984	1.336	1.305	-2.32
Pb	600.7	0.155	1.000	1.000	-	-
	700.0	0.175	1.167	1.129	1.052	-6.84
	800.0	0.192	1.333	1.239	1.103	-10.96
Sn	505.1	0.303	1.000	1.000	-	-
	600.0	0.323	1.188	1.066	1.058	-0.72
	700.0	0.344	1.386	1.135	1.120	-1.35
	800.0	0.364	1.584	1.201	1.181	-1.66
	873.2	0.378	1.728	1.248	1.226	-1.79

[a] Calculated according to Equation (27) with C = 0.31

are temperature and melting temperature in K, and C represents the linear coefficient. The coefficient, C, was found to be 0.31 from the data given in Table 9 by a least-square technique. The comparison of calculated thermal conductivities with the experimental values in Table 9 showed that Eq. (27) can be used for engineering purposes for estimating the thermal conductivities of molten metals for the small temperature regions adjacent to the melting temperatures, when experimental data are not available. The general test of Eq. (27) for the thermal conductivities of liquid alloys was not possible, since the available experimental data for the liquid alloys are very limited. However, Eq. (27) was tested for liquid Na-K alloy. The calculated thermal conductivities according to Eq. (27) were found to be within 7% of the experimental values[16] for temperatures up to 1.5 times the melting temperature.

An estimation was made for the thermal conductivities of stainless steels Type 304L and Type 316L in the liquid region by using the above correlations. At the melting points, the thermal conductivities of solid steels were reduced by half to give the values in the liquid state. Then, Eq. (27) with C = 0.31 was used to evaluate the thermal conductivity values above the melting temperatures.

Thermal conductivities of stainless steels thus estimated in the liquid region and those provided by the experimental data in the solid region are represented by the following functional equations:

Type 304L:

$$k = 8.116\times10^{-2} + 1.618\times10^{-4}\ T \qquad \text{(solid region)} \qquad (28)$$

$$k = 1.229\times10^{-1} + 3.248\times10^{-5}\ T \qquad \text{(liquid region)} \qquad (29)$$

Type 316L:

$$k = 9.248\times10^{-2} + 1.571\times10^{-4}\ T \qquad \text{(solid region)} \qquad (30)$$

$$k = 1.241\times10^{-1} + 3.279\times10^{-5}\ T \qquad \text{(liquid region)} \qquad (31)$$

where k = thermal conductivity in W/(cm)(K) and T = temperature in K.

Thermal diffusivities of stainless steels have been calculated from the values of thermal conductivity, density, and specific heat using the definition of thermal diffusivity:

$$\text{thermal diffusivity} = \frac{\text{thermal conductivity}}{\text{density x specific heat}} \qquad (32)$$

The thermal diffusivity values thus derived are represented by the following functional equations:

Type 304L:

$$a = 2.276\times10^{-2} + 3.285\times10^{-5}\ T - 2.762\times10^{-9}\ T^2 \qquad \text{(solid region)} \qquad (33)$$

$$a = 2.514\times10^{-2} + 1.996\times10^{-7}\ T + 2.386\times10^{-9}\ T^2 \qquad \text{(liquid region)} \qquad (34)$$

Type 316L:

$$a = 2.578\times10^{-2} + 3.265\times10^{-5}\ T - 3.138\times10^{-9}\ T^2 \quad \text{(solid region)} \quad (35)$$

$$a = 2.686\times10^{-2} - 4.812\times10^{-7}\ T + 2.580\times10^{-9}\ T^2 \quad \text{(liquid region)} \quad (36)$$

where a = thermal diffusivity in cm^2/sec and T = temperature in K.

Recommended values of thermal conductivity and thermal diffusivity of stainless steels Type 304L and Type 316L are given in Table 10 and Figs. 7 and 8.

E. Viscosity

Experimental data for the viscosity of stainless steels are not available. However, the viscosity of iron was reported[10] for temperatures up to 2200K. These values in Ref. 10 had been selected from several sets of experimental data. We extrapolated these values to 3000 K, and for all practical purposes, the data may be used for the viscosities of stainless steels because most of the transport properties of stainless steels are governed chiefly by those of iron, the major constituent of steels.

Recommended values of both stainless steels Type 304L and Type 316L are represented by the following equation:

$$\log \mu = \frac{2385.2}{T} - 0.5958 \quad (37)$$

where μ = viscosity in cP, and T = temperature in K. The viscosity values of stainless steels are also given in Table 11 and Fig. 9.

III. CONCLUDING REMARKS

Thermodynamic properties and transport properties of the low-carbon stainless steels Type 304L and Type 316L were evaluated for the temperature range between 300 and 3000 K, and given in the forms of functional equations, tables, and graphs.

The property values in the solid region were obtained by extrapolating available experimental data to the melting range. Least-square techniques were used to smooth experimental data points. When the data were not available for low-carbon stainless steels, the existing values for regular stainless steels were used instead. The only difference in compositions between low-carbon and regular stainless steels is the maximum carbon content. Both low-carbon stainless steels are allowed 0.03 wt % carbon at most, whereas Type 304 and Type 316 stainless steels contain 0.08 wt % and 0.10 wt % carbon, respectively. In the evaluation of thermophysical properties, it was assumed that this small difference in carbon content between low-carbon and regular stainless steels is negligible. On this basis, the data presented in this report may be used for both regular and low-carbon stainless steels.

Appropriate correlations were used in estimating the properties of steels in the liquid region. Thermodynamic properties, which include enthalpy, entropy, specific heat and vapor pressure, were evaluated by

TABLE 10. Thermal Conductivities and Thermal Diffusivities of Stainless Steels Type 304L and Type 316L

Temperature (K)	Type 304L Conductivity [W/(cm) (K)]	Type 304L Diffusivity $x10^2(cm^2/sec)$	Type 316L Conductiyity [W/(cm) (K)]	Type 316L Diffusivity $x10^2(cm^2/sec)$
300	0.1297	3.237	0.1396	3.529
400	0.1459	3.546	0.1553	3.834
500	0.1620	3.849	0.1710	4.132
600	0.1782	4.148	0.1868	4.424
700	0.1944	4.440	0.2025	4.710
800	0.2106	4.727	0.2182	4.989
900	0.2267	5.009	0.2339	5.262
1000	0.2429	5.285	0.2496	5.529
1100	0.2591	5.555	0.2653	5.190
1200	0.2753	5.820	0.2810	6.044
1300	0.2914	6.080	0.2967	6.292
1400	0.3076	6.334	0.3125	6.534
1500	0.3238	6.582	0.3282	6.769
1600	0.3400	6.825	0.3439	6.999
1700(s)	0.3561	7.062	0.3596	7.222
1700(ℓ)	0.1781	3.238	0.1798	3.350
1800	0.1814	3.323	0.1831	3.435
1900	0.1846	3.413	0.1864	3.526
2000	0.1879	3.508	0.1897	3.622
2100	0.1911	3.608	0.1930	3.723
2200	0.1944	3.713	0.1962	3.829
2300	0.1976	3.822	0.1995	3.940
2400	0.2009	3.936	0.2028	4.057
2500	0.2041	4.055	0.2061	4.178
2600	0.2073	4.179	0.2094	4.305
2700	0.2106	4.307	0.2126	4.437
2800	0.2138	4.441	0.2159	4.574
2900	0.2171	4.579	0.2192	4.716
3000	0.2203	4.721	0.2225	4.864

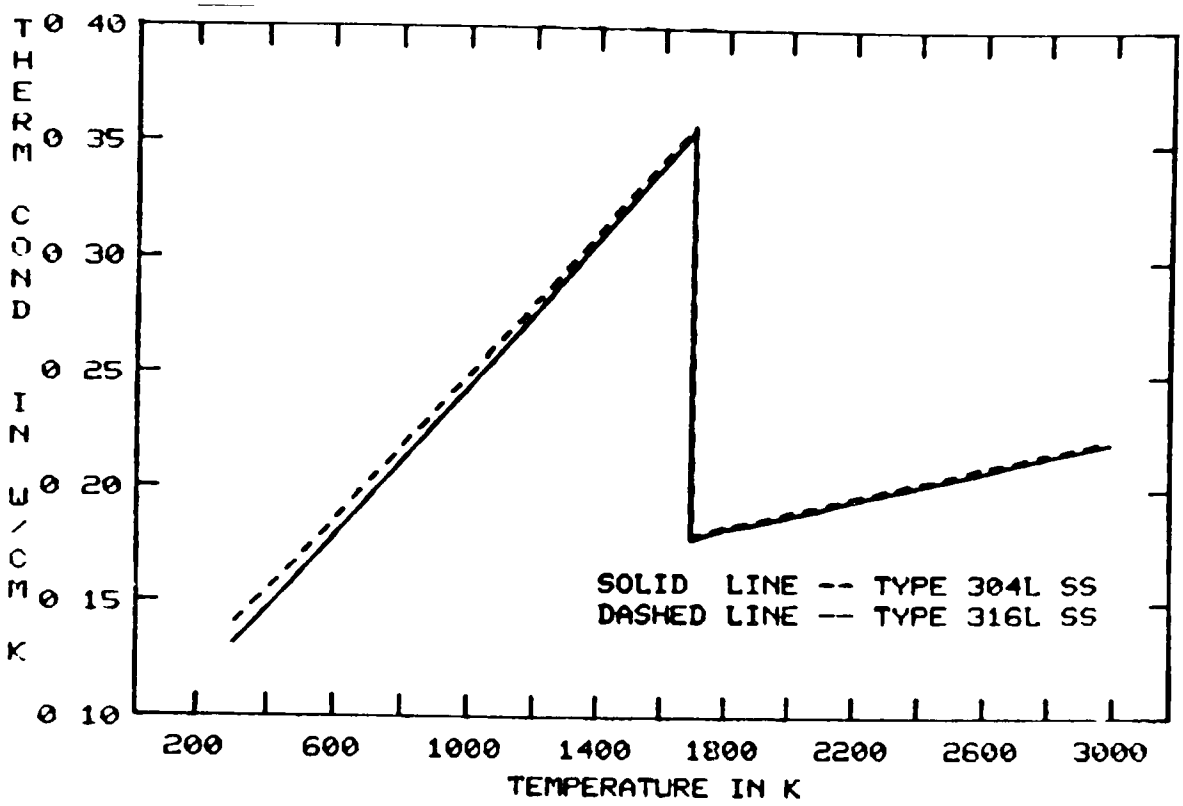

Fig. 7. Thermal Conductivities of Stainless Steels *vs.* Temperature.

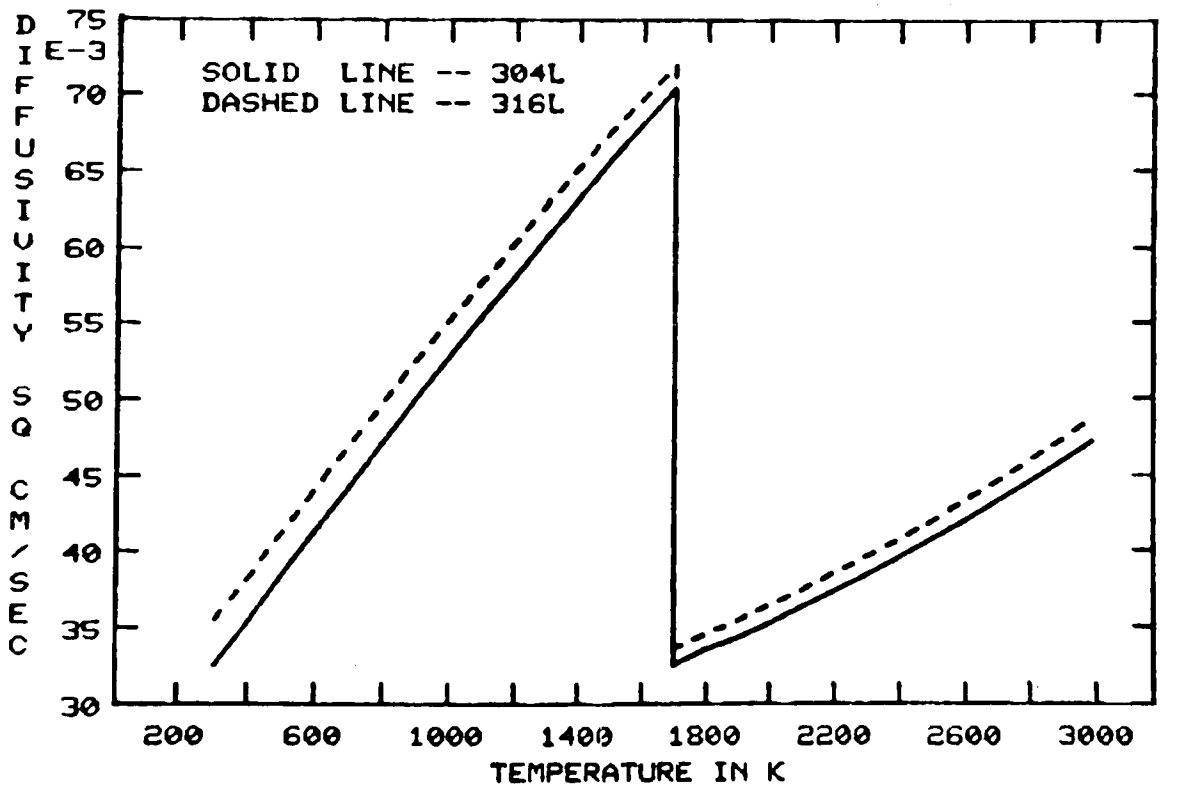

Fig. 8. Thermal Diffusivities of Stainless Steels *vs.* Temperature.

TABLE 11. Viscosities of Stainless Steels

Temperature (K)	Viscosity (cP)	Temperature (K)	Viscosity (cP)
1700	6.42	2400	2.50
1800	5.36	2500	2.28
1900	4.57	2600	2.10
2000	3.95	2700	1.94
2100	3.47	2800	1.80
2200	3.08	2900	1.69
2300	2.76	3000	1.58

applying the additivity rule to the available data for these properties of the major constituent elements. In these estimations, stainless steel Type 304L was considered to be composed of 72% Fe, 19% Cr, and 9% Ni, and Type 316L, of 19% Fe, 17% Cr, 12% Ni, and 2% Mo, by weight. In other words, stainless steel Type 304L was treated as being composed of 0.713, 0.202, and 0.085 atom fractions of Fe, Cr, and Ni, respectively, and Type 316L, of 0.691, 0.183, 0.114, and 0.012 atom fractions of Fe, Cr, Ni, and Mo, respectively.

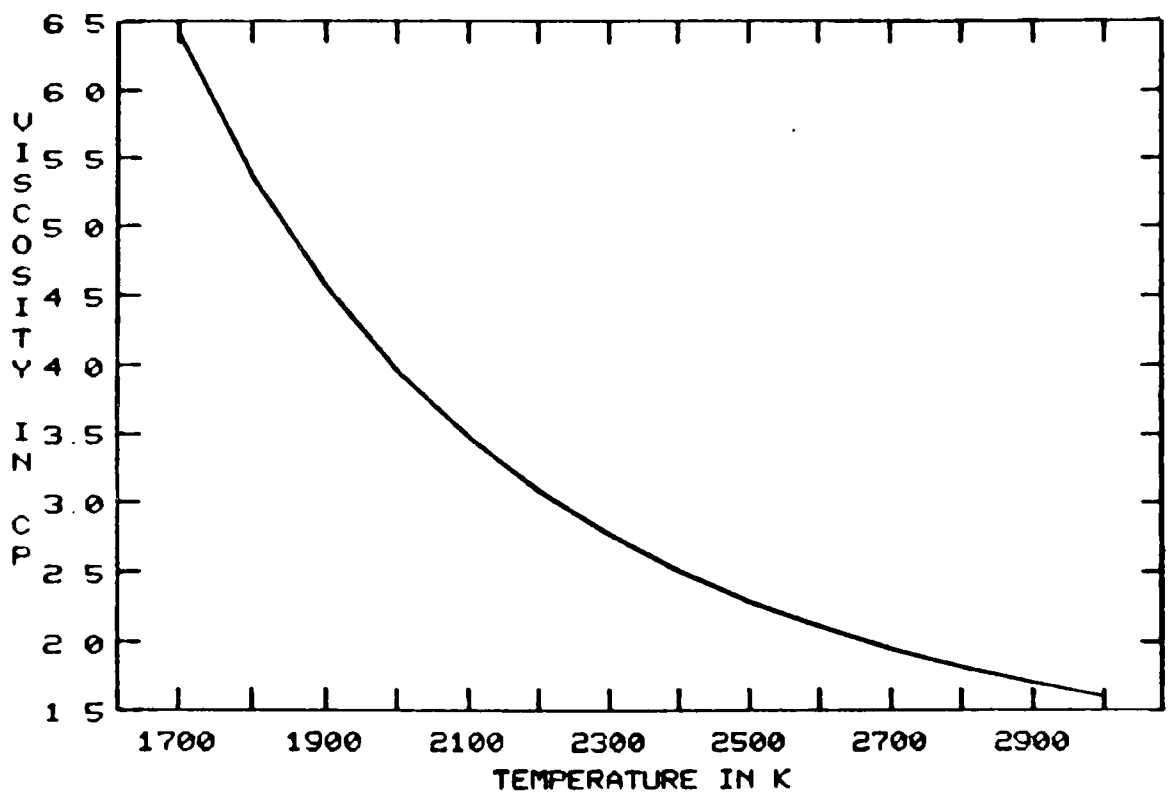

Fig. 9. Viscosities of Stainless Steels *vs.* Temperature.

Transport properties evaluated include density, thermal expansion coefficient, thermal conductivity, thermal diffusivity, and viscosity. Densities of molten stainless steels were calculated according to the formula empirically derived from the existing low-temperature data for the alloys. The correlations on thermal conductivity changes due to melting and temperature dependencies of liquid thermal conductivities were derived from the available data for several molten metal elements. The correlations were used in estimating thermal conductivities of stainless steels in the liquid region. Thermal expansion coefficient and thermal diffusivity values were calculated according to their definitions using other property values previously evaluated. There being no data for the viscosity of steels, data for iron were extrapolated to 3000 K. These data are recommended for the stainless steels on the basis that most transport properties in steel are governed by the iron component.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Dr. L. Leibowitz for many valuable discussions. The author also wishes to thank Dr. F. A. Cafasso for his interest in this work.

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