Equations for the Calculation of the Thermo-physical Properties of Stainless Steel

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Equations have been derived to calculate values of the thermophysical properties of all stainless steels for temperatures between 300 and 1 800 K (austenitic 3 series, ferritic-4 series and precipitation-hardened 6-series alloys). Values of the following properties are given in both figures and tables: density (ρ), thermal expansion coefficient (α), heat capacity (C_p), enthalpy (H_f−H_298), thermal conductivity (λ) and thermal diffusivity (a), electrical resistivity (R), viscosity (η) and surface tension (γ).

KEY WORDS: stainless steels; thermo-physical properties; density; surface tension; viscosity; heat capacity; enthalpy; thermal and electrical conductivity.

1. Introduction

Stainless steels play an important part in modern living since they have good corrosion resistance and a pleasing appearance. There are several types of stainless steel (typical compositions are given in Table 1):

- 3 series contain Cr and Ni and usually contain Mo; they have a metastable, austenitic structure
- 4 series contain Cr (but no Ni since this stabilises the austenite) and have a ferritic structure but martensitic phases can be formed in some cases (e.g. 410) when oil-quenched or air-cooled
- 6-series are precipitation-hardened alloys and tend to contain Cr and Ni in lower amounts

Mathematical modelling has become an established tool for improving process control and product quality. However, it has been shown that accurate thermophysical property data are needed for reliable predictions of defects[1] or improved product quality (e.g. Weld profiles in TIG/GTA welding[2,3]). This study seeks to provide reliable thermo-physical property data for all types of stainless steels.

The principal objective of this work was to establish equations which provide reliable values for thermo-physical properties for the full range of stainless steels. The general approach adopted here makes use of fact that the thermo-physical properties of Fe, Cr and Ni are very similar; thus differences in Ni% and Cr% in different stainless steels do not have a significant effect on the property value.

It should be noted that ferritic and martensitic (i.e. 4-series alloys) undergo a magnetic transition and subsequently transform to austenite. The values of properties, such as density and enthalpy, are little affected by these transitions but their temperature coefficients, i.e. heat capacity (C_p) and thermal expansion coefficient (α), respectively, along with the thermal diffusivity do vary appreciably. Consequently, in these cases, it is not always possible to give one equation to cover all the properties for all types of stainless steel.

Thermal and electrical conductivity (or resistivity) values are affected by the microstructure of the solid sample which is, in turn, dependent upon the heat treatment and the cold work given to the alloy. In these cases the thermal conductivity and electrical resistivity refer to samples with the maximum conductivity or minimum resistance. Property values based on the various recommended equations are given at the end of the paper in Tables 3 and 4.

The liquidus temperatures, T_liquidus of the various types of stainless steels were estimated using the coefficients recommended by Howe.[4] The calculated values are shown in Table 1. It has been assumed in Table 3 that liquidus temperature of 3- and 6-series alloys occurs at 1 723 K and for 4-series alloys at 1 773 K.

2. Density (ρ), Thermal Expansion Coefficient (α)

2.1. Database

Thermal expansion data have been reported by Bogaard et al.[5] for austenitic 304 steel and ferritic 430 stainless...
steels. Density data for solid 304, 316, 410 and 446 stainless steels are cited by Touloukian and by Mills for 304 and 316. Density data for the liquid 316 alloy have been reported by McCormick and Brooks and for 430 by Li et al.

Experimental uncertainties for measurements are probably \(<2\%\) for density (\(\rho\)) and \(<10\%\) for the linear thermal expansion coefficient (\(\alpha\)).

2.2. Analysis of Data

- Thermal Expansion Coefficient (\(\alpha\))

Bogaard et al. report data which gives the following equation for austenitic 304 steel:

\[
\alpha (K^{-1}) = 15.8 + 0.6 \times 10^{-2}(T - 298) \quad \ldots \ldots (1)
\]

As can be seen from Fig. 1, at temperatures below 1 000 K, the ferritic phase (in 430) has a lower \(\alpha\) than that for austenite (in 304); above 1 000 K the austenite formed results in a higher \(\alpha\) value. Thus the thermal expansion for ferritic alloys can be calculated using Eqs. (2) and (3).

\[
T = (298 - 1000) \quad \alpha (K^{-1}) = 10.2 + 0.6 \times 10^{-2}(T - 298 K) \quad \ldots (2)
\]

\[
T = (1000 - 1 700) \quad \alpha (K^{-1}) = 14.2 + 2.4 \times 10^{-2}(T - 1 000 K) \quad \ldots (3)
\]

- Densities (\(\rho\))

Densities were first calculated by assuming that the following equation applied:

\[
\rho = \sum x_i \rho_i = \sum x_i \rho_x \quad \ldots (4)
\]

where \(x\) = mole fraction and that 1, 2, 3 etc. refer to different metallic components. In actual fact this relation is more correct when using the molar volume, \(V\), than for density, \(\rho\), but the errors associated with the above assumption are small.

Numerical analysis of the experimental density data gave the following equations:

Solid:

\[
\rho_s = (79.6\% \text{Fe}) + (78.3\% \text{Cr}) + (85.4\% \text{Ni}) + (76.9\% \text{Mn}) + (60.2\% \text{Mo}) + (47.1\% \text{Si}) - 0.5(T - 298 K) \quad \ldots (5)
\]

Liquid:

\[
\rho_l = (69.4\% \text{Fe}) + (66.3\% \text{Cr}) + (71.4\% \text{Ni}) + (57.2\% \text{Mn}) + (51.5\% \text{Mo}) + (49.3\% \text{Si}) - 0.86(T - 1 823 K) \quad \ldots (6)
\]

Equation (5) makes use of an average value for \(\alpha\); more exact values can be obtained by removing the \(-0.5(T - 298 K)\) term from Eq. (5) and dividing the remainder of the equation by \((1 + 3\alpha(T - 298 K))\) where \(\alpha\) can be calculated by Eq. (1) for austenitic alloys and by Eqs. (2) and (3) for ferritic alloys. However, values calculated using Eq. (5) with this procedure were found to lie within 0.5% of those calculated by the more rigorous treatment.

The calculated densities are in good agreement with the experimental values (Fig. 2). It should be noted that the values were calculated using Eq. (5). The liquid density values for 4-series alloys shown in Fig. 3 and Table 3(b) may be very slightly low for temperatures between 1 723 and 1 900 K. Vinet has reported a value of \(\rho = 6.980 \text{ kg m}^{-3}\) for 316L at \(T_{\text{eq}}\) which is about 1% higher than the values calculated from Eq. (6), but lies within the band of experimental uncertainty.

3. Heat Capacity (\(C_p\), Enthalpy (\(H_f - H_{298}\))

3.1. Database

Heat capacity data for 304 and 316 stainless steels have been reported by Bogaard et al. and by Mills. The experimental uncertainty is probably about \(\pm 2\%\) at temperatures below 1 000 K and \(\pm 5\%\) at temperatures in the range 1 000 to 1 700 K. Ferritic alloys exhibit a magnetic transformation leading to a peak in the \(C_p\) around 1 000 K as can be
tend to vary. However, the enthalpy, \((H_f - H_{f298})\) values are little affected and apply reasonably well to both ferritic and austenitic alloys. Values for the liquid were derived from the experimental values reported by Chapman et al.\(^{12,13}\).

The entropy of fusion, \(\Delta S_{\text{fus}}\) for the steel can be estimated from values of \(\Delta S_{\text{fus}}\) for different elements using a similar relation to that in Eq. (4).

### 3.3. Results and Discussion

Solid:

\[
C_p(JK^{-1}kg^{-1}) = 472 + 13.6 \times 10^{-2} T - 2.82 \times 10^6 / T^2 \tag{10}
\]

\[
(H_f - H_{f298})(Jkg^{-1}) = 472T + 6.8 \times 10^{-2} T^2 + 2.82 \times 10^6 / T - 156000 \tag{11}
\]

Liquid:

\[
C_p = 800 \pm 50 J K^{-1} kg^{-1} \tag{12}
\]

\[
\Delta S_{\text{fus}} = \Delta H_{\text{fus}} / T_{\text{liq}} = 160 J K^{-1} kg^{-1} \tag{13}
\]

It can be seen from the results shown in Figs. 4 and 5 that there is good agreement between the values calculated with Eqs. (10) to (13). The uncertainty associated with the calculation of \(C_p\) and \((H_f - H_{f298})\) is probably less than 5%.

### 4. Thermal Conductivity (λ)

Thermal conductivity data for most solid alloys are sensitive to the microstructure. Consequently, these values are, in turn, dependent upon the thermal and mechanical histories of the samples. These effects are relatively small in the case of stainless steels because of their relatively low thermal conductivities (cf. Al alloys, where it can make a significant difference).

#### 4.1. Database

Thermal conductivities have been reported by the following:

- Bogaard et al.\(^{3,4}\) for alloys, 304, 321 and 430; Chu and Ho\(^{31}\) for 410 and 430; Bogaard\(^{14}\) for 3-series and 631 and Mills\(^{5}\) for alloys 304 and 316. The values cited below relate to the maximum thermal conductivity. Values for the liquid phase are based on those reported by Mills.\(^{7}\)

#### 4.2. Analysis of Data

**4.2.1. Method 1**

The thermal conductivity contains contributions from both lattice and electronic conductivities (Eq. (14)) and the electronic conductivity at 300 K can be calculated from the electrical resistivity, \(R\) by use of the Wiedemann–Franz–Lorenz relation (Eq. (15)) where \(L_o\) is constant with a value of \(2.445 \times 10^{-8}\).

\[
\lambda_{300} = \lambda_{300}^l + \lambda_{300}^e \tag{14}
\]

\[
\lambda_{300}^e = L_o T / R_{300} \times 10^6 \tag{15}
\]

The resistivity, \(R_{300}\) can be calculated from Eq. (16) using the values given in Table 2 due to Mills et al.\(^{11}\) The unit of \(R_{300}\) is \(10^{-6} \Omega m\).

\[
R_{300} = (1/100) \sum (\text{wt}\% R_{300})_i + (\text{wt}\% R_{300})_2 + (\text{wt}\% R_{300})_3 + \ldots \tag{16}
\]
where subscripts 1, 2, 3 refer to Fe, Cr, Ni etc.

The lattice conductivities ($\lambda_{\text{lat}}$) can be calculated in a similar manner using Eq. (17) and the values given in Table 2 due to Mills et al.\(^{11}\)

\[
\Lambda_{300} = (1/100) \sum (\text{wt\%} \cdot \lambda_{300})_1 + (\text{wt\%} \cdot \lambda_{300})_2 + (\text{wt\%} \cdot \lambda_{300})_3 
\]

The thermal conductivity of the alloy at 300 K is then calculated using Eq. (14).

The thermal conductivity–temperature relation was constructed by joining $\lambda_{300}$ to the following values: 27.6 W m\(^{-1}\) K\(^{-1}\) at 1 273 K, 30.2 W m\(^{-1}\) K\(^{-1}\) at 1 473 K and 32.8 W m\(^{-1}\) K\(^{-1}\) at 1 673 K.

Experimental thermal conductivity values for both 3- and 4-series stainless steels are similar at high temperatures (>1 100 K), therefore an average value at each temperature has been used.

4.2.2. Method 2

Equation (18) is a “best fit” equation for the experimental $\lambda$ data for austenitic 3-series alloys as a function of temperature.

\[
\lambda (\text{W m}^{-1} \text{K}^{-1}) = 9.2 + 0.0175 T - 2 \times 10^{-6} T^2 
\]

In the case of 4 series alloys there are appreciable differences between the values reported for alloys 410 and 430. Consequently, mean values were used in deriving a ‘best fit’ equation

Ferritic: Below 1 100 K

\[
\lambda (\text{W m}^{-1} \text{K}^{-1}) = 23.5 + 0.0016(T - 300) \quad (19)
\]

All alloys above 1 100 K

\[
\lambda (\text{W m}^{-1} \text{K}^{-1}) = 25.4 + 1.3 \times 10^{-2}(T - 1 100) \quad (20)
\]

4.3. Results and Discussion

The results show that the differences between experimental and calculated values are within 5%, for the 3-series alloys and for the alloy 410 but are more than 10% divergent for 430. It can be seen from Figs. 6 and 7 that the thermal conductivities of ferritic, 4-series alloys are higher than those for austenitic 3-series alloys.

5. Thermal Diffusivity ($a$)

Thermal diffusivities for the solid state, like thermal conductivities, are dependent upon the microstructure and are thus influenced by the thermal and mechanical history of the sample. Furthermore, thermal diffusivity values for ferritic alloys are influenced by the magnetic transition ($a = \lambda / \rho C_p$). Values for the liquid were derived from values of thermal conductivity.

5.1. Database

Thermal diffusivity values have been reported for 304 by Bogaard et al.,\(^{31}\) Monaghan\(^{35}\) and Szegadowski\(^{66}\) (as reported by Mills\(^{71}\)) and by Seetharaman.\(^{17}\) Thermal diffusivities can be calculated by $a = \lambda / \rho C_p$ but are frequently measured directly (with the laser pulse method). The measurements of thermal diffusivities of ferritic steels go through a minimum around 1 000 K ($a = \lambda / C_p \rho$): this corresponds to the peak in the $C_p$–$T$ relation. Touloukian\(^{6}\) has reported thermal diffusivity values for 403, 410, 416, 420 and 430 alloys, all of which exhibit a minimum value around 970 K.

5.2. Results and Discussion

The thermal diffusivity values shown in Figs. 8 and 9 refer to austenitic, 3-series and to ferritic, 4-series alloys, respectively, these were calculated from the recommended values of $\Lambda$, $C_p$, and $\rho$. In Fig. 8 calculated values for 3 series alloys are compared with the experimental values reported by Mills\(^{71}\) and by Seetharaman.\(^{17}\) It can be seen that the calculated values are within 10% of the experimental

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### Table 2. Coefficients used in the calculation of thermal conductivity.\(^{11}\)

<table>
<thead>
<tr>
<th>Element</th>
<th>Fe</th>
<th>Cr</th>
<th>Si</th>
<th>Mn</th>
<th>Mo</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{300,10^3}$ (Ω m(^{-1}))</td>
<td>0.11</td>
<td>0.0192</td>
<td>0.0091</td>
<td>0.0353</td>
<td>0.0097</td>
<td>0.0211</td>
</tr>
<tr>
<td>$\Lambda_{\text{lat}}$, W m(^{-1}) K(^{-1})</td>
<td>8.1</td>
<td>0.00347</td>
<td>-0.968</td>
<td>0.0011</td>
<td>0.00391</td>
<td>-0.00283</td>
</tr>
</tbody>
</table>

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values. The values for 4-series, ferritic alloys shown in Fig. 9 indicate that the calculated values are very sensitive to the \(C_p\) values used in the region of the magnetic transition. Nevertheless, the calculated values lie within 10% of experimental values for 4 series alloys.

6. Electrical Resistivity (\(R\))

6.1. Database

Electrical resistivity (\(R\)) data have been reported by Bogaard et al.\(^5\) for alloys 303, 304, 316, 317, 321, 347 and 410 and 430 and for alloys 316, 631 and 660 by Ho et al.\(^13\) The electrical resistivity is dependent upon the microstructure and hence the thermal and mechanical histories of the sample; the equations relate to samples with the lowest resistivity.

6.2. Analysis of Data

The electrical resistivity (\(R\)) data were assumed to have a similar temperature dependence to that of the enthalpy, namely, \(R = a' + b'T + c'T^2\). Thus “best fit” equations in this form were derived from the mean experimental data\(^5\) for 304, 316 and 410 and 430 alloys.

6.3. Results and Discussion

The electrical resistivities of the ferritic (4 series) alloys at temperatures below 1 000 K are lower than those of the austenitic (3 series) and 6-series alloys. Best fit expressions for \(R (10^{-3}\ \Omega\ \text{m}^{-1})\):

Austenitic (3-, 6-series)

\[
R (10^{-3}\ \Omega\ \text{m}^{-1}) = 51.9 + 8.6 \times 10^{-2}T - 2.35 \times 10^{-5}T^2
\]

\[\text{.........................................(21)}\]

Ferritic (4 series)

\[
R (10^{-3}\ \Omega\ \text{m}^{-1}) = 23.8 + 12.9 \times 10^{-2}T - 4.17 \times 10^{-5}T^2
\]

\[\text{.........................................(22)}\]

It can be seen from Fig. 10 that there is good agreement between the values calculated with Eqs. (21) and (22) and the experimental data. Values calculated via Eq. (16) and Table 2 vary by <5% from the experimental values.

7. Surface Tension (\(\gamma\))

The surface tensions of alloys are very dependent upon the levels of soluble oxygen and sulphur (denoted \(O\) and \(S\)). The soluble \(O\) is also dependent upon the Al content of the metal (see Fe–Al–O curve in Fig. 11\(^3\)). Although the Al contents of stainless steels are usually quite low, they are sufficiently high in most cases to keep the \(O\) content constant at a level of about 5 ppm. Thus the surface tension is primarily dependent upon the \(S\) content of the steel.

7.1. Database

Surface tension data have been reported for alloys 304

\[\]
and 316 as functions of temperature and sulphur content by Brooks et al.\(^{(19)}\) and for alloy 430 by Li et al.\(^{(9)}\) The experimental uncertainty associated with the surface tension measurements is probably around \(\pm 3\%\).

7.2. Analysis of Data

The method has been described in more detail elsewhere.\(^{(19)}\) The method assumes that:

(a) The differing Cr and Ni contents of the various stainless steels have little effect on the surface tension of the pure metal. \(\gamma_{\text{pure}}\) (i.e. with zero O or S content) since the surface tensions of Fe, Cr and Ni are all very similar. The following equation was adopted for the “pure” metal.

\[
\gamma_{\text{pure}} (\text{mN m}^{-1}) = 1 \, 840 - 0.4 (T - 1 \, 823 \, \text{K}) \quad \ldots \ldots (23)
\]

(b) The soluble O is fixed at 5 ppm by the Al content of the steel and thus variations in temperature are dependent only on the S content and temperature.

(c) The effect of S on the surface tension had the form (first proposed by Belton\(^{(20)}\))

\[
\gamma_{\text{pure}} - \gamma_{\text{ss}} = R^* T \Gamma_0 \ln(1 + K_s \alpha_s) \quad \ldots \ldots (24)
\]

where \(R^*\) = Gas constant, \(\Gamma_0\) = surface excess concentration, \(K_s\) = equilibrium constant for the absorption of S on the metal and \(\alpha_s\) = activity coefficient of S in Fe (\(= 0.68\) wt\% S\(^{(19)}\)).

The following procedures were employed to analyse the data reported by Brooks et al.\(^{(18)}\) and Li et al.\(^{(9)}\)

(i) \(\Gamma_0\) was determined from the limiting slope of the plot of the surface tension of steel against \(\ln \alpha_s\) (i.e. the values at higher S contents where the surface is saturated with S were adopted).

(ii) A mean value for \(\Gamma_0\) was derived from values calculated from the surface tension data due to Li et al.\(^{(9)}\) and Brooks et al.\(^{(18)}\)

(iii) This mean value was used in Eq. (24) to derive values for \(K_s\).

(iv) The temperature dependence of \(K_s\) was derived by plotting the various values of \(\ln K_s\) as a function of \(1/T (\ln K_s = \ln k_s + A/T)\) where \(k_s\) = pre-exponential term and \(A=\Delta_{\text{act}} H / R^*\).

\[
\ln K_s = (28 \, 798/T) \, - 8.5647 \quad \ldots \ldots (25)
\]

(v) The temperature dependence \((d\gamma/dT)\) was determined by differentiating the Eq. (26) and is given in Eq. (27).

7.3. Results and Discussion

The following equations were derived

\[
\gamma = 1 \, 840 - 0.4 (T - 1 \, 823) - 0.056 T \ln\{1 + e^{(28 \, 798/T - 8.5647)/0.68\text{wt\%S}}\} \quad \ldots \ldots (26)
\]

\[
\frac{d\gamma}{dT} = -0.4 - 0.056 \left( \frac{28 \, 798(1 - B)}{BT} + \ln B \right) \quad \ldots \ldots (27)
\]

where \(B = 1 + e^{(28 \, 798/T - 8.5647)/0.68\text{wt\%S}}\).

The surface tension values calculated with Eqs. (26) and (27) are compared with the experimental values reported by Li et al.\(^{(9)}\) and by Brooks et al.\(^{(18)}\) in Figs. 12(a) and 12(b), respectively. It can be seen that calculated values are in good agreement and also with the value reported by Seetharaman et al.\(^{(17)}\) (Calculated \(\gamma = 1 \, 793 \text{mN m}^{-1}\) compared with a measured value of 1790 mN m\(^{-1}\) at 1866 K.) The calculated values are within 3% of the experimental results. The calculated values for the temperature dependence \((d\gamma/dT)\) are compared with those reported by Brooks et al.\(^{(18)}\) and with those calculated by McNallen and Debroy\(^{(21)}\) in Fig. 13 and can be seen to provide reasonable values of \((d\gamma/dT)\).

Calculated values of the surface tension of stainless steels with different amounts of S are shown as a function of temperature in Fig. 14 and Table 4.

8. Viscosity (\(\eta\))

8.1. Database

The viscosity values shown in Eq. (28) were obtained by Brooks et al.\(^{(23)}\) for a stainless steel (25.6% Cr, 6.5% Ni and
4% Mo) using oscillation viscometry. These results were used in this study. The measured values at 1873 K are higher for the alloy than those for pure Fe (e.g. 6.25 mPa·s cf. 5.2 mPa·s for Fe). The uncertainties in the reported measurements for pure Fe and other metals are large but recent measurements obtained with oscillation viscometry23-25) fall within a band of ±10% (e.g. \( \eta(Fe) = 5.2 \pm 0.3 \text{ mPa·s} \) and \( \eta(Ni) = 4.1 \pm 0.4 \text{ mPa·s} \) at 1873 K). Thus the viscosities of the major components Fe, Cr and Ni are probably very similar and the thermodynamics of the Fe–Cr, Fe–Ni systems are close to ideal. However, with commercial alloys it has been reported that the presence of non-metallic inclusions can cause an increase in viscosity.26,27) Consequently, measurements on commercial materials like stainless steels are subject to greater uncertainty and to more variability than those for pure metals.

![Fig. 14. Calculated values of surface tension of stainless steel with various S content as a function of temperature.](image1)

![Fig. 15. Viscosities of stainless steel as function of reciprocal temperature.22)](image2)

### Table 3. Calculated values of the thermophysical properties of stainless steels—where 2 sets of values are given e.g. 481 (452)—the first value 481 refers to \( C_p \) of the austenitic steel and (452) to \( C_p \) of the ferritic-phase steel.

<table>
<thead>
<tr>
<th>T/K</th>
<th>( \rho / \text{ kg/m}^3 )</th>
<th>( C_p / \text{ J/kg°C} )</th>
<th>( (H_1+H_2) / \text{ kJ/kg} )</th>
<th>( \lambda / \text{ Wm}^{-1} \text{ K}^{-1} )</th>
<th>( 10^6 \alpha / \text{ m}^2 \text{s}^{-1} )</th>
<th>( 10^8 \beta / \text{ Ωm}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>298.2</td>
<td>7921</td>
<td>481 (452)</td>
<td>0</td>
<td>14.2 (23.5)</td>
<td>3.74 (6.59)</td>
<td>75.5 (58.6)</td>
</tr>
<tr>
<td>400</td>
<td>7870</td>
<td>509 (481)</td>
<td>50.7</td>
<td>15.9 (23.7)</td>
<td>3.96 (6.27)</td>
<td>82.5 (68.7)</td>
</tr>
<tr>
<td>500</td>
<td>7820</td>
<td>529 (527)</td>
<td>103</td>
<td>17.4 (23.8)</td>
<td>4.22 (5.80)</td>
<td>89.0 (77.9)</td>
</tr>
<tr>
<td>600</td>
<td>7770</td>
<td>546 (577)</td>
<td>156</td>
<td>19.0 (24.0)</td>
<td>4.47 (5.37)</td>
<td>95.0 (86.2)</td>
</tr>
<tr>
<td>700</td>
<td>7720</td>
<td>561 (628)</td>
<td>212</td>
<td>20.5 (24.1)</td>
<td>4.72 (5.00)</td>
<td>100.6 (93.7)</td>
</tr>
<tr>
<td>800</td>
<td>7670</td>
<td>576 (686)</td>
<td>269</td>
<td>21.9 (24.3)</td>
<td>4.96 (4.64)</td>
<td>105.7 (100.3)</td>
</tr>
<tr>
<td>900</td>
<td>7620</td>
<td>591 (858)</td>
<td>327</td>
<td>23.3 (24.5)</td>
<td>5.18 (3.76)</td>
<td>110.3 (106.1)</td>
</tr>
<tr>
<td>1000</td>
<td>7570</td>
<td>605 (1067)</td>
<td>387</td>
<td>24.7 (24.6)</td>
<td>5.39 (3.06)</td>
<td>114.4 (111.1)</td>
</tr>
<tr>
<td>1100</td>
<td>7520</td>
<td>619 (728)</td>
<td>448</td>
<td>26.0 (25.4)</td>
<td>5.59 (4.69)</td>
<td>118.1 (115.2)</td>
</tr>
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<td>1200</td>
<td>7470</td>
<td>633</td>
<td>511</td>
<td>27.3</td>
<td>5.78</td>
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<td>7420</td>
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<td>575</td>
<td>28.6</td>
<td>5.95</td>
<td>122.5</td>
</tr>
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<td>1400</td>
<td>7370</td>
<td>661</td>
<td>640</td>
<td>29.8</td>
<td>6.11</td>
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<tr>
<td>1500</td>
<td>7320</td>
<td>675</td>
<td>707</td>
<td>30.9</td>
<td>6.26</td>
<td>126.3</td>
</tr>
<tr>
<td>1600</td>
<td>7270</td>
<td>688</td>
<td>775</td>
<td>32.1</td>
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<td>126.3</td>
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<td>33.2</td>
<td>6.54</td>
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<td>894</td>
<td>34.1</td>
<td>6.63</td>
<td>126.7</td>
</tr>
<tr>
<td>1800</td>
<td>7194</td>
<td>7209</td>
<td>894</td>
<td>34.1</td>
<td>6.63</td>
<td>126.7</td>
</tr>
<tr>
<td>1900</td>
<td>6756</td>
<td>800</td>
<td>1283</td>
<td>30</td>
<td>5.5</td>
<td>5.98</td>
</tr>
</tbody>
</table>

Uncertainty ±5% ±5% ±5% ±10% ±10% ±10%

a. The values in magnetic transition range may be subject to error.
b. For ferritic 4-series alloys only

c. Liquid phase
8.2. Analysis of Data
It was assumed that the viscosities of Fe, Cr and Ni are very similar. Consequently, the experimental viscosity values for a stainless steel given in Eq. (28) will apply to all stainless steels.

8.3. Results and Discussion
The results due to Brooks et al. can be represented by Eq. (28) and are shown in Fig. 15:

\[ \ln \eta (\text{mPa} \cdot \text{s}) / H_{11005} (H_{11002} / H_{11001} 2.396 / H_{11001} 7950 / T) \] .............(28)

Estimated values derived from the relation due to Hirai et al. are significantly lower than the experimental values. (e.g. 3.6 cf. 6.25 mPa \cdot s, respectively at 1 873 K).

9. Summary
The calculated values of the thermophysical properties of the solid and liquid phases are given in Tables 3(a) and 3(b) respectively. The calculated values for the surface tension for various temperatures and S contents are given in Table 4.

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