



IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors

IEEE Power Engineering Society

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IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors

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**Transmission and Distribution Committee
of the
IEEE Power Engineering Society**

Approved 16 November 2006

IEEE-SA Standards Board

Abstract: A method of calculating the current-temperature relationship of bare overhead lines, given the weather conditions, is presented. Along with a mathematical method, sources of the values to be used in the calculation are indicated. This standard does not undertake to list actual temperature-ampacity relationships for a large number of conductors, but rather provides a standard method of doing such calculations.

Keywords: bare overhead lines, current-temperature relationship

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Introduction

This introduction is not part of IEEE Std 738-2006, IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors.

In 1986, IEEE Std 738-1993, IEEE Standard for Calculation of Bare Overhead Conductor Temperature and Ampacity Under Steady-State Conditions, was first published. The standard was developed “so that a practical sound, and uniform method (of calculation) might be utilized and referenced.” As part of the revision in 1993, the Working Group on the Calculation of Bare Overhead Conductor Temperatures, which was responsible for the revision of this standard, decided to address fault current and transient ratings and include their calculation in this standard.

In the present revision, SI units were added throughout, the solar heating calculation was extensively revised, and many editorial changes were made.

Consistent with IEEE guidelines for standards such as this, SI units are used exclusively in the main body. “English” units are used in Annex A since they are widely utilized by power transmission line design engineers in North America.

This standard includes a computer program listing to serve as a basis for program development. The working group has made every effort to ensure that the program yields accurate results. The user is cautioned that there may be values of rating parameters for which the method is not appropriate.

Many persons have contributed to the preparation, analysis, and review of this standard. We would like to recognize the contribution of the late B.S. Howington, who served as chair of the working group for many years and was responsible for developing the original standard. Richard E. Kennon, James Larkey, Jerry Reding, and Dale Douglass (Task Force Chairman) did most of the revisions in the latest version of the standard. Many of the other Working Group members contributed their time and thought. Catherine Berger, an IEEE staff editor, was immensely helpful in getting the standard completed in an acceptable format.

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IEEE Standard for Calculating the Current-Temperature of Bare Overhead Conductors

1. Overview

1.1 Scope

The purpose of this standard is to present a method of calculating the current-temperature relationship of bare overhead conductors.

Conductor surface temperatures are a function of the following:

- a) Conductor material properties
- b) Conductor diameter
- c) Conductor surface conditions
- d) Ambient weather conditions
- e) Conductor electrical current

The first two of these properties are specific chemical and physical properties. The third may vary with time and be dependent upon ambient atmospheric conditions other than weather. The fourth, weather, varies greatly with the hour and season. The fifth, conductor electrical current, may be constant or may vary with power system loading, generation dispatch, and other factors.

The equations relating electrical current to conductor temperature may be used in either of the following two ways:

- To calculate the conductor temperature when the electrical current is known
- To calculate the current that yields a given maximum allowable conductor temperature

For the purposes of this standard, either the electrical current is assumed constant for all time or it is assumed to undergo a step change from an initial current to a final current. The ambient weather conditions are assumed to be constant with time in both the steady-state and transient calculation methods described in this standard.

This standard includes mathematical methods and indicates sources of the values to be used in the calculation of conductor temperatures and conductor thermal ratings. However, because there is a great diversity of weather conditions and operating circumstances for which conductor temperatures and/or thermal ratings must be calculated, the standard does not undertake to list actual temperature-current relationships for specific conductors or weather conditions. Each user must make their own assessment of which weather data and conductor characteristics best pertain to their area or particular transmission line.

The calculation methods in this standard are also valid for the calculation of conductor temperature under fault conditions.

1.2 Disclaimer

A computer program is included in this standard as a convenience to the user. Other numerical methods may well be more appropriate in certain situations.

The IEEE Conductors Working Group of the Towers, Poles, and Conductors Subcommittee has made every effort to ensure that the program yields accurate calculations under anticipated conditions; however, there may well be certain calculations for which the method is not appropriate. It is the responsibility of the user to check calculations against either test data or other existing calculation methods.

2 Definitions

For the purposes of this document, the following terms and definitions apply. The Authoritative Dictionary of IEEE Standard Terms [B21]¹ should be referenced for terms not defined in this clause.

2.1 conductor temperature: The temperature of a conductor is assumed to be isothermal (i.e., no axial or radial temperature variation) for all steady-state calculations and for all transient calculations where the time period of interest exceeds 1 min or the conductor consists of a single material. With transient calculations for times less than 1 min with non-homogeneous aluminum conductor steel reinforced (ACSR) conductors, the aluminum strands are isothermal, but the heat capacity of the steel core is assumed to be zero.

2.2 heat capacity (material): When the conductor temperature is increased by dT_c as a result of adding a quantity of heat dQ_c , the ratio, dQ_c/dT_c , is the heat capacity of the conductor.

2.3 maximum allowable conductor temperature: The maximum temperature limit that is selected in order to minimize loss of strength, sag, line losses, or a combination of the above.

2.4 Reynolds number: A non-dimensional number equal to air velocity (V_w) times conductor diameter (D) divided by kinematic viscosity (μ/ρ_f).

2.5 specific heat: The specific heat of a conductor material is its heat capacity divided by its mass.

2.6 steady-state thermal rating: The constant electrical current that would yield the maximum allowable conductor temperature for specified weather conditions and conductor characteristics under the assumption that the conductor is in thermal equilibrium (steady state).

¹ The numbers in brackets correspond to those of the bibliography in Annex H

2.7 thermal time constant: The time required for the conductor temperature to accomplish 63.2% of a change in initial temperature to the final temperature when the electrical current going through a conductor undergoes a step change.

2.8 transient thermal rating: The transient thermal rating is that final current (I_f) that yields the maximum allowable conductor temperature (T_c) in a specified time after a step change in electrical current from some initial current, I_i .

2.9 wind direction: The direction of the movement of air relative to the conductor axis. The wind direction and the conductor axis are assumed to be in a plane parallel to the earth. When the wind is blowing parallel to the conductor axis it is termed “parallel wind.” When the wind is blowing perpendicularly to the conductor axis, it is termed “perpendicular wind.”

3. Temperature calculation methods

The Working Group on the Calculation of Bare Overhead Conductor Temperatures has conducted a study on the various methods used in calculating heat transfer and ampacities of transmission line conductors. Methods that were studied include the methods contained in the following publications:

- a) House and Tuttle [B20]
- b) ECAR, House and Tuttle method as modified by East Central Area Reliability [B29]
- c) Mussen [B24]
- d) Pennsylvania-New Jersey-Maryland Interconnection [B11]
- e) Schurig and Frick [B25]
- f) Hilpert [B17]
- g) Davis [B9]
- h) Morgan [B22]
- i) Black and Bush [B3]
- j) Black and Byrd [B4]
- k) Foss, Lin, and Fernandez [B15]

The mathematical models of this standard are based upon the House and Tuttle method as modified by ECAR [B29]. The House and Tuttle formulas consider all of the essential factors without the simplifications that were made in some of the other formulas.

To differentiate between laminar and turbulent air flow, the House and Tuttle method [B20] uses two different formulas for forced convection; the transition from one to the other is made at a Reynolds number of 1000. Because turbulence begins at some wind velocity and reaches its peak at some higher velocity, the transition from one curve to another is a curved line, not a discontinuity. The single transition value was selected as a convenience in calculating conductor ampacities.

The single transition value results in a discontinuity in current magnitude when this value is reached. Therefore, to avoid this discontinuity that occurs using the House and Tuttle method [B20], ECAR [B29] elected to make the change from laminar to turbulent air flow at the point where the curves developed from

the two formulas [Equation (3a) and Equation (3b)] cross. The formulas for forced convection heat loss have an upper limit of application validity at a Reynolds number of 50 000 (see McAdams [B22]). For additional information on convection heat loss, see 4.2 of this standard.

The primary application of this standard is anticipated to be the calculation of steady-state and transient thermal ratings and conductor temperatures under constant weather conditions. Given the widespread availability of desktop personal computers, the calculation method specified avoids certain simplifications that might be advisable where the speed or complexity of calculations is important.

In Davis [B9], the heat balance equation is expressed as a biquadratic equation that can be solved to give the conductor temperature directly. In Black and Rehberg [B5] and Wong, et al. [B30], the radiation term is linearized and the resulting approximate linearized heat balance equation is solved using standard methods of linear differential equations. In Foss [B14], a somewhat more precise linearized radiation term is used to reduce the number of iterations required. These methods are computationally faster than the iterative method described in this standard; however, the algebraic expressions are more complex.

3.1 Steady-state calculations

3.1.1 Steady-state thermal rating

For a bare stranded conductor, if the conductor temperature (T_c) and the steady-state weather parameters (V_w , T_a , etc.) are known, the heat losses due to convection and radiation (q_c and q_r), the solar heat gain (q_s), and the conductor resistance $R(T_c)$ can be calculated by the formulas of 3.4. The corresponding conductor current (I) that produced this conductor temperature under these weather conditions can be found from the steady-state heat balance [Equation (1b) of 3.4.1]. While this calculation can be done for any conductor temperature and any weather conditions, a maximum allowable conductor temperature (e.g., 75 °C to 150 °C) and “conservative” weather conditions (e.g., 0.6 m/s to 1.2 m/s wind speed, 30 °C to 45 °C summer ambient)² are often used to calculate a steady-state thermal rating for the conductor.

3.1.2 Steady-state conductor temperature

Since the radiation and convection heat loss rates are not linearly dependent on the conductor temperature, the heat balance equation [Equation (1b) of 3.4.1] is solved for conductor temperature in terms of the current and weather variables by a process of iteration—that is, given a conductor current,

- a) A conductor temperature is assumed.
- b) The corresponding heat losses are calculated.
- c) The conductor current that yields this conductor temperature is calculated by means of Equation (1b).
- d) The calculated current is compared to the given conductor current.
- e) The conductor temperature is then increased or decreased until the calculated current equals the given current.

² This wind speed in English units would be 2 ft/s to 4 ft/s.

3.2 Transient calculations

3.2.1 Transient conductor temperature

The temperature of an overhead power conductor is constantly changing in response to changes in electrical current and weather. In this standard, however, weather parameters (wind speed and direction, ambient temperature, etc.) are assumed to remain constant; and any change in electrical current is limited to a step change from an initial current, I_i , to a final current, I_f , as illustrated in Figure 1.

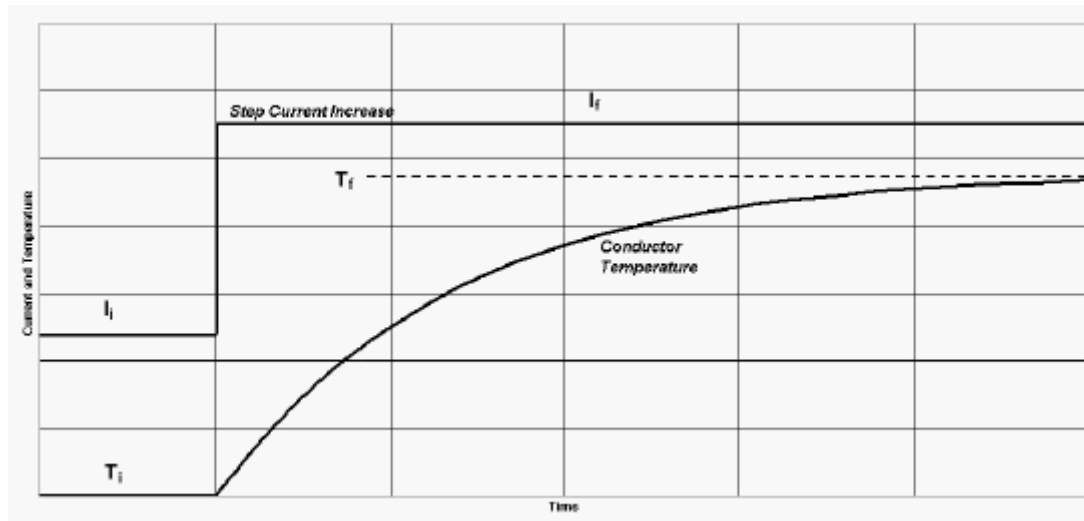


Figure 1— “Step” change in current

Immediately prior to the current step change ($t = 0^-$), the conductor is assumed to be in thermal equilibrium. That is, the sum of heat generation by Ohmic losses and solar heating equals the heat loss by convection and radiation.

Immediately after the current step change ($t = 0^+$), the conductor temperature is unchanged (as are the conductor resistance and the heat loss rate due to convection and radiation), but the rate of heat generation due to Ohmic losses has increased. Therefore, at time $t = 0^+$, the temperature of the conductor begins to increase at a rate given by the non-steady-state heat balance Equation (2b) in 3.4.2.

After a period of time, Δt , the conductor temperature has increased by a temperature change of ΔT_c . The increased conductor temperature yields higher heat losses due to convection and radiation and somewhat higher Ohmic heat generation due to the increased conductor resistance. From Δt to $2\Delta t$, the conductor temperature continues to increase, but does so at a lower rate. After a large number of such time intervals, the conductor temperature approaches its final steady-state temperature (T_f).

During each interval of time, the corresponding increase in conductor temperature may be calculated using the formulas given in 3.4. The computer program included in Annex B calculates the conductor temperature as a function of time after the step change in current.

Accuracy in the iterative transient calculation requires that the time step chosen be sufficiently small with respect to the thermal time constant. It is always prudent to rerun the calculation with a smaller time step to check whether the calculated values change.

3.2.2 Transient thermal rating

The transient thermal rating is normally calculated by repeating the preceding calculations of $T_c(t)$ over a range of I_f values, then selecting the I_f value that causes the conductor temperature to reach its maximum allowable value in the allotted time.

3.2.3 Fault current calculations

Conductor temperature changes in response to “fault” currents are calculated in the same manner as in 3.2.1, except that the step increase in current is usually quite large ($>10\,000$ A), the corresponding time to reach maximum allowable temperature is typically short (<1 s), and the maximum temperatures attained may approach the melting point of aluminum or copper.

With nonhomogeneous conductors, such as aluminum conductor steel reinforced (ACSR), the heat generation in the lower conductivity steel core is much lower than in the surrounding aluminum strand layers. The resulting temperature difference between the core and the surrounding aluminum strands abates after no more than 60 s from any step change in current. This is discussed further in 3.4.8.

3.3 Units and identification of letter symbols

NOTE—SI units are the preferred unit of measure. However, in the United States the calculations described in this standard have frequently been performed using a combination of units that will be referred to throughout this document as “English” units. See Annex A for an analysis using these units.³

Table 1—Units and identification of letter symbols

Symbol	Description	SI units
A'	Projected area of conductor per unit length	m^2/m
C	Solar azimuth constant	degrees
C_{pi}	Specific heat of i^{th} conductor material	$\text{J}/(\text{kg}\cdot^{\circ}\text{C})$
D	Conductor diameter	mm
H_c	Altitude of sun	degrees
H_e	Elevation of conductor above sea level	m
I	Conductor current	A
I_i	Initial current before step change	A
I_f	Final current after step change	A
K_{angle}	Wind direction factor	—
K_{solar}	Solar altitude correction factor	—
k_f	Thermal conductivity of air at temperature T_{film}	$\text{W}/(\text{m}\cdot^{\circ}\text{C})$
Lat	Degrees of latitude	degrees
mC_p	Total heat capacity of conductor	$\text{J}/(\text{m}\cdot^{\circ}\text{C})$
m_i	Mass per unit length of i^{th} conductor material	kg/m
N	Day of the year (January 21 = 21, February 12 = 43, etc.)	—
$q_{\text{cns}}, q_{\text{c1}}, q_{\text{c2}}, q_{\text{c}}$	Convected heat loss rate per unit length	W/m
q_r	Radiated heat loss rate per unit length	W/m

³ Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.

Table 1—Units and identification of letter symbols (*continued*)

Symbol	Description	SI units
q_s	Heat gain rate from sun	W/m
Q_s	Total solar and sky radiated heat flux rate	W/m ²
Q_{se}	Total solar and sky radiated heat flux rate elevation corrected	W/m ²
$R(T_c)$	AC resistance of conductor at temperature, T_c	Ω /m
T_a	Ambient air temperature	°C
T_c	Conductor temperature	°C
T_f	Conductor temperature many time constants after step increase	°C
T_i	Conductor temperature prior to step increase	°C
T_{film}	$(T_c + T_a)/2$	°C
T_{low}	Minimum conductor temperature for which ac resistance is specified	°C
T_{high}	Maximum conductor temperature for which ac resistance is specified	°C
V_w	Speed of air stream at conductor	m/s
Z_c	Azimuth of sun	degrees
Z_l	Azimuth of line	degrees
Δt	Time step used in transient calculation	s
ΔT_c	Conductor temperature increment corresponding to time step	°C
α	Solar absorptivity (0.23 to 0.91)	—
δ	Solar declination (0 to 90)	degrees
ε	Emissivity (0.23 to 0.91)	—
τ	Thermal time constant of the conductor	s
ϕ	Angle between wind and axis of conductor	degrees
β	Angle between wind and perpendicular to conductor axis	degrees
ρ_f	Density of air	kg/m ³
θ	Effective angle of incidence of the sun's rays	degrees
μ_f	Dynamic viscosity of air	Pa-s
ω	Hours from local sun noon times 15	degrees
χ	Solar azimuth variable	—

3.4 Formulas

3.4.1 Steady-state heat balance

$$q_c + q_r = q_s + I^2 R(T_c) \quad (1a)$$

$$I = \sqrt{\frac{q_c + q_r - q_s}{R(T_c)}} \quad (1b)$$

3.4.2 Non-steady-state heat balance

$$q_c + q_r + mC_p \frac{dT_c}{dt} = q_s + I^2 R(T_c) \quad (2a)$$

$$\frac{dT_c}{dt} = \frac{1}{mC_p} [R(T_c)I^2 + q_s - q_c - q_r] \quad (2b)$$

3.4.3 Forced convection heat loss rate

NOTE—The English unit equivalents of these equations can be found in A.2.1.

$$q_{cl} = \left[1.01 + 0.0372 \left(\frac{D\rho_f V_w}{\mu_f} \right)^{0.52} \right] k_f K_{\text{angle}} (T_c - T_a) \quad (3a)$$

$$q_{c2} = \left[0.0119 \left(\frac{D\rho_f V_w}{\mu_f} \right)^{0.6} k_f K_{\text{angle}} (T_c - T_a) \right] \quad (3b)$$

Equation (3a) applies at low winds but is incorrect at high wind speeds. Equation (3b) applies at high wind speeds, being incorrect at low wind speeds. At any wind speed, the larger of the two calculated convection heat loss rates is used.

The convective heat loss rate is multiplied by the wind direction factor, K_{angle} , where ϕ is the angle between the wind direction and the conductor axis [see Equation (4a)].

$$K_{\text{angle}} = 1.194 - \cos(\phi) + 0.194 \cos(2\phi) + 0.368 \sin(2\phi) \quad (4a)$$

Alternatively, the wind direction factor may be expressed as a function of the angle, β , between the wind direction and a perpendicular to the conductor axis. This angle is the complement of ϕ , and the wind direction factor becomes as shown in Equation (4b).

$$K_{\text{angle}} = 1.194 - \sin(\beta) - 0.194 \cos(2\beta) + 0.368 \sin(2\beta) \quad (4b)$$

This is the form of the wind direction factor as originally suggested in Davis [B9] and is used in the computer program listed in Annex B.

3.4.4 Natural convection

With zero wind speed, natural convection occurs, where the rate of heat loss is as shown in Equation (5).

$$q_{cn} = 0.0205 \rho_f^{0.5} D^{0.75} (T_c - T_a)^{1.25} \quad (5)$$

NOTE—The English unit equivalent of this equation can be found in A.2.2.

It has been argued that at low wind speeds, the convection cooling rate should be calculated by using a vector sum of the wind speed and a “natural” wind speed, see Morgan [B23]. However, it is recommended that only the larger of the forced and natural convection heat loss rates be used at low wind speeds instead of their vector sum as this is conservative. The computer program listed in Annex B takes this approach.

For both forced and natural convection, air density (ρ_f), air viscosity (μ_f), and coefficient of thermal conductivity of air (k_f) are taken from Table 1 or calculated with the equations of 3.5 at T_{film} where:

$$T_{film} = \frac{T_c + T_a}{2} \quad (6)$$

3.4.5 Radiated heat loss rate

$$q_r = 0.0178 D \epsilon \left[\left(\frac{T_c + 273}{100} \right)^4 - \left(\frac{T_a + 273}{100} \right)^4 \right] \quad (7)$$

NOTE—The English unit equivalent of this equation can be found in A.2.3.

3.4.6 Rate of solar heat gain (see Table 4, Table 5, and Table 6)

$$q_s = \alpha Q_{sc} \sin(\theta) A' \quad (8)$$

where

$$\theta = \arccos[\cos(H_c) \cos(Z_c - Z_l)] \quad (9)$$

NOTE—The English unit equivalent of this equation can be found in A.2.4.

3.4.7 Conductor electrical resistance

The electrical resistance of bare stranded conductor varies with frequency, average current density, and temperature. For 60 Hz ac, at temperatures of 25 °C to 75 °C, the *Aluminum Electrical Conductor Handbook* [B1] gives calculated values of electrical resistance for most standard aluminum power conductors.

These calculated values include the frequency-dependent “skin effect” for all types of stranded conductor, but, for other than single-layer ACSR, do not include a correction for current density dependent magnetic core effects, which is significant for ACSR conductors having odd numbers of layers of aluminum strands. The resistance of single-layer ACSR conductors (6/1, 7/1, 12/7) is shown to be increased as much as 20% in the *Aluminum Electrical Conductor Handbook* [B1]. The resistance of three-layer ACSR (45/7, 54/7, etc.) may be as much as 3% higher than the tabulated values. Engineering judgment is required in thermal calculations involving these ACSR conductors.

Resistance at temperatures above 75 °C may be calculated according to the methods described in the *Aluminum Electrical Conductor Handbook* [B1], Black and Bush [B3], and Douglass, et al. [B12].

In this standard, electrical resistance is calculated solely as a function of conductor temperature; however, the resistance values entered may be a function of frequency and current density. For example, the values of conductor resistance at high temperature, T_{high} , and low temperature, T_{low} , may be taken from the

tabulated values in the *Aluminum Electrical Conductor Handbook* [B1]. The conductor resistance at any other temperature, T_c , is found by linear interpolation according to Equation (10).

$$R(T_c) = \left[\frac{R(T_{\text{high}}) - R(T_{\text{low}})}{T_{\text{high}} - T_{\text{low}}} \right] (T_c - T_{\text{low}}) + R(T_{\text{low}}) \quad (10)$$

This method of resistance calculation allows the user to calculate the high and low temperature resistance values by whatever means is appropriate.

Since the resistivity of most common metals used in stranded conductors increases somewhat faster than linearly with temperature, the resistance calculated by Equation (10) will be somewhat high (and thus conservative for rating calculations) so long as conductor temperature is between T_{low} and T_{high} . If the conductor temperature exceeds T_{high} , however, the calculated resistance will be somewhat low (and thus non-conservative for rating calculations). For example, based upon measurements of individual 1350 H19 aluminum strand resistance for a temperature range of 20 °C to 500 °C, entry of resistance values at temperatures of 25 °C and 75 °C will yield estimates of conductor resistance that are approximately 1% and 5% lower than measured values at temperatures of 175 °C and 500 °C, respectively. Between 25 °C and 75 °C, the error is negligible. Similarly, entry of resistance values at temperatures of 25 °C and 175 °C, will yield estimates that are approximately 3% too low at 500 °C but 0.5% too high at 75 °C.

It is concluded that the use of resistance data for temperatures of 25 °C and 75 °C from the *Aluminum Electrical Conductor Handbook* [B1] is adequate for rough calculations of steady-state and transient thermal ratings for conductor temperatures up to 175 °C, and may be used for approximate fault calculations up to the melting point of typical conductor materials.

3.4.8 Conductor heat capacity

Conductor heat capacity is defined as the product of specific heat and mass per unit length. If the conductor consists of more than one material (e.g., ACSR), then the heat capacities of the core and the outer strands are each defined in this way.

For transient thermal rating calculations with durations of 5 min to 30 min, the temperature of the conductor components remains approximately equal after the step increase in current. The heat capacity of the conductor can be calculated as the sum of the component heat capacities as shown in Equation (11).

$$mC_p = \sum m_i C_{pi} \quad (11)$$

Values for the specific heat of common metals used in stranded overhead conductors are listed in Black and Rehberg [B5] and in 4.6 of this standard.

With a nonhomogeneous conductor, for faults with durations of less than 60 s, the internal temperature difference between the core and the outer strands can be neglected. In particular, for ACSR conductor, the heat capacity of the relatively nonconducting steel core should be neglected for step currents whose duration is less than 60 s. For step currents whose duration is greater than 60 s, the heat capacity of the core is included. For step current durations of 10 s to 60 s, the calculated conductor temperatures are somewhat conservative because any temperature difference between the core and outer strands decreases to zero with an internal thermal time constant of the order of 10 s to 20 s.

3.5 Equations for air properties, solar angles, and solar heat flux

In the following section, least square polynomial regressions were performed on tabular data for thermal conductivity (3.5.3), total heat flux (3.5.6), and solar heat correction for elevation (3.5.7) to fit an equation of the following form:

$$Y = A + BX + CX^2 + DX^3 + EX^4 + FX^5 + GX^6$$

Algebraic equations are given for viscosity (3.5.1), density (3.5.2), solar altitude (3.5.4), azimuth (3.5.5).

Tables of typical values are provided for convenience.

3.5.1 Dynamic viscosity of air

The dynamic viscosity of air is determined by the algebraic equation listed in Equation (12).

$$\mu_f = \frac{1.458 \times 10^{-6} (T_{\text{film}} + 273)^{1.5}}{T_{\text{film}} + 383.4} \quad (12)$$

NOTE—The English unit equivalent of this equation can be found in A.3.1.

3.5.2 Air density (Table 2)

$$\rho_f = \frac{1.293 - 1.525 \times 10^{-4} H_e + 6.379 \times 10^{-9} H_e^2}{1 + 0.00367 T_{\text{film}}} \quad (13)$$

NOTE—The English unit equivalent of this equation can be found in A.3.2.

3.5.3 Thermal conductivity of air (Table 2)

$$k_f = 2.424 \times 10^{-2} + 7.477 \times 10^{-5} T_{\text{film}} - 4.407 \times 10^{-9} T_{\text{film}}^2 \quad (14)$$

NOTE—The English unit equivalent of this equation can be found in A.3.3.