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Table of Contents

1. Introduction

The Thermophysics Facilities Branch (Code ASF) of the Space Technology Division of NASA Ames Research Center, located in Moffett Field, CA, operates the Arc Jet Complex for the investigation of atmospheric entry and high-velocity phenomena. The Ames Arc Jet Complex comprises of four active arc jet facilities: the Aerodynamic Heating Facility (AHF), the Interaction Heating Facility (IHF), the Panel Test Facility (PTF) and the 2x9 Turbulent Flow Duct Facility (TFD). Data collected from all four facilities are processed through the Arc Jet Data Acquisition Systems. These systems record instrument outputs and provide initial conversion to engineering units.

2. Purpose

The Arc Jet Measurement System Handbook will serve as a reference of the calculations and formulas used by the Arc Jet Complex Data Acquisition System. It is the objective that Code ASF personnel and experimenters will be able to manually reproduce data calculations performed by the Arc Jet Data Acquisition System using these formulas as a guide.

3. Scope

This document has been prepared to inform all personnel conducting tests at the Arc Jet Complex of the details regarding Data System calculation methods. It is designed to serve as a supplemental reference guide detailing formulas and calculations used in the data system.

4. Engineering Unit Conversions

This section is provided to convert engineering units between various units of measure. Currently, engineering and scientific data from the Arc Jet Complex Data Acquisition System is reduced in SI units.

Unit conversion equations provided by:

Standard for Use of the International System of Units (SI): The Modern Metric System, IEEE/ ASTM SI 10-1997, New York, NY, 1997.

National Institute of Standards and Technology: Guide for the Use of International System of Units (SI) Webbook, http://physics.nist.gov/Pubs/SP811/contents.html

4.1 Temperature

Start with:	***Conversion:***	***To Obtain:***
Celsius (°C) [t_C]	$t_F = 1.8\ t_C + 32$	Fahrenheit (°F) [t_F]
Celsius (°C) [t_C]	$T_K = 273.15 + t_C$	Kelvin (K) [T_K]
Celsius (°C) [t_C]	$T_R = 1.8\ t_C + 491.67$	Rankine (°R) [T_R]
Fahrenheit (°F) [t_F]	$t_C = 5/9\ (t_F - 32)$	Celsius (°C) [t_C]
Fahrenheit (°F) [t_F]	$T_K = 5/9\ (t_F + 459.67)$	Kelvin (K) [T_K]
Fahrenheit (°F) [t_F]	$T_R = 459.67 + t_F$	Rankine (°R) [T_R]
Kelvin (K) [T_K]	$t_C = T_K - 273.15$	Celsius (°C) [t_C]
Kelvin (K) [T_K]	$t_F = 1.8\ T_K - 459.67$	Fahrenheit (°F) [t_F]
Kelvin (K) [T_K]	$T_R = 1.8\ T_K$	Rankine (°R) [T_R]
Rankine (°R) [T_R]	$t_C = 5/9\ T_R - 273.15$	Celsius (°C) [t_C]
Rankine (°R) [T_R]	$t_F = T_R - 459.67$	Fahrenheit (°F) [t_F]
Rankine (°R) [T_R]	$T_K = 5/9\ T_R$	Kelvin (K) [T_K]

4.2 Pressure

Start with:	*Multiply by:*	*To Obtain:*
Kilopascal (Kpa)	9.869233E-03	Atmosphere (atm)
Kilopascal (Kpa)	0.1450377	Pound / Inch^2 (psi)
Kilopascal (Kpa)	7.500617	Torr
Torr	1.315789E-02	Atmosphere (atm)
Torr	0.1333224	Kilopascal (Kpa)
Torr	1.933677E-02	Pound / Inch^2 (psi)
Atmosphere (atm)	101.325	Kilopascal (Kpa)
Atmosphere (atm)	14.69595	Pound / Inch^2 (psi)
Atmosphere (atm)	760	Torr
Pound / Inch^2 (psi)	6.804596E-02	Atmosphere (atm)
Pound / Inch^2 (psi)	6.894757	Kilopascal (Kpa)
Pound / Inch^2 (psi)	51.71493	Torr

4.3 Heat Flux

Start with:	*Multiply by:*	*To Obtain:*
W / cm^2	0.8805507	BTU / (sec • ft^2)
W / m^2	8.805507E-5	BTU / (sec • ft^2)
W / cm^2	0.0001	W / m^2
BTU / (sec • ft^2)	1.135653	W / cm^2

4.4 Length

Start with:	***Multiply by:***	***To Obtain:***
millimeter (mm)	3.937008E-02	inch (in)
millimeter (mm)	3.28084E-03	foot (ft)
millimeter (mm)	0.1	centimeter (cm)
millimeter (mm)	0.001	meter (m)
centimeter (cm)	0.3937008	inch (in)
centimeter (cm)	3.28084E-02	foot (ft)
centimeter (cm)	10	millimeter (mm)
centimeter (cm)	0.01	meter (m)
meter (m)	39.37008	inch (in)
meter (m)	3.28084	foot (ft)
meter (m)	1000	millimeter (mm)
meter (m)	100	centimeter (cm)
inch (in)	8.333333E-02	foot (ft)
inch (in)	25.4	millimeter (mm)
inch (in)	2.54	centimeter (cm)
inch (in)	0.0254	meter (m)
foot (ft)	12	inch (in)
foot (ft)	304.8	millimeter (mm)
foot (ft)	30.48	centimeter (cm)
foot (ft)	0.3048	meter (m)

4.5 Density

Start with:	Multiply by:	To Obtain:
gram / centimeter^3	3.612729E-02	pound / inch^3
gram / centimeter^3	62.42796	pound / foot^3
gram / centimeter^3	1,000,000	gram / meter^3
gram / centimeter^3	1000	kilogram / meter^3
gram / meter^3	3.61273E-08	pound / inch^3
gram / meter^3	6.24280E-05	pound / foot^3
gram / meter^3	1.00E-06	gram / centimeter^3
gram / meter^3	0.001	kilogram / meter^3
kilogram / meter^3	3.61E-05	pound / inch^3
kilogram / meter^3	6.242796E-02	pound / foot^3
kilogram / meter^3	0.001	gram / centimeter^3
kilogram / meter^3	1000	gram / meter^3
pound / inch^3	1728	pound / foot^3
pound / inch^3	27.6799	gram / centimeter^3
pound / inch^3	27.6799E+07	gram / meter^3
pound / inch^3	27679.9	kilogram / meter^3
pound / foot^3	5.78704E-04	pound / inch^3
pound / foot^3	1.601846E-02	gram / centimeter^3
pound / foot^3	16018.46	gram / meter^3
pound / foot^3	16.01846	kilogram / meter^3

4.6 Viscosity

Start with:	Multiply by:	To Obtain:
kg / m / s	0.671968975	lb / ft / s
lb / ft / s	1.488163944	kg / m / s

4.7 Mass Flow

Start with:	***Multiply by:***	***To Obtain:***
gram / sec	2.204623E-03	pound / sec
gram / sec	0.132277357	pound / min
gram / sec	0.06	kilogram / min
gram / min	3.6744E-05	pound / sec
gram / min	2.204623E-03	pound / min
gram / min	1.6667E-05	kilogram / sec
kilogram / sec	2.204622622	pound / sec
kilogram / sec	132.2773573	pound / min
kilogram / sec	60	kilogram / min
kilogram / min	3.674371E-02	pound / sec
kilogram / min	2.204622622	pound / min
kilogram / min	1.6666667E-02	kilogram / sec
pound / sec	60	pound / min
pound / sec	0.45359237	kilogram / sec
pound / sec	27.2155422	kilogram / min
pound / min	1.6666667E-02	pound / sec
pound / min	7.559873E-03	kilogram / sec
pound / min	0.45359237	kilogram / min

4.8 Volumetric Flow

Start with:	***Multiply by:***	***To Obtain:***
liter / min	0.2641721	gallon / min
liter / min	0.03531467	$foot^3$ / min
liter / min	0.001	$meter^3$ / min
gallon / min	3.785412	liter / min
gallon / min	0.1336806	$foot^3$ / min
gallon / min	3.785412E-03	$meter^3$ / min
$foot^3$ / min	28.31685	liter / min
$foot^3$ / min	7.480519	gallon / min
$foot^3$ / min	0.02831685	$meter^3$ / min
$meter^3$ / min	1000	liter / min
$meter^3$ / min	264.1721	gallon / min
$meter^3$ / min	35.31467	$foot^3$ / min

5. Temperature Conversions

The Arc Jet Complex Data Acquisition System is capable of utilizing moderate temperature (base metal types: K, J, T, E and N), high temperature (platinum types: R, S, and B), and extreme temperature (tungsten types: C, D, and G) thermocouples. The following method is used to convert microvolt readings from a thermocouple to temperature units.

Thermocouple voltage signals are converted into temperature units (in this case, °C) by calculations using the appropriate equations for the thermocouple type that are valid for the temperature range.

The Data Acquisition System performs cold junction compensation by measuring a reference temperature for the junction, converting it to a microvolt signal that would be produced by a reference thermocouple of the same type, and then adding the reference microvolt signal to the thermocouple microvolt signal. The reference compensated signal is then converted to a temperature measurement.

For measurement values that fall within an overlap of equations, the Data System applies the lower bound microvolt conversion for the higher temperature range. Although the conversions for a thermocouple type consist of a number of equations, the continuity of the conversion is very nearly piecewise smooth.

Thermocouple Millivolts to Temperature Conversions provided by:

ASTM Committee E20 on Temperature Measurement, Manual on the Use of Thermo-couples in Temperature Measurement, 4th ed., ASTM, Ann Arbor, MI, 1993, pp. 192-211.

The International Temperature Scale of 1990 (ITS-90), Bureau International des Poids et Measures, Ottawa, Canada, 1989.

The Annual Book of ASTM Standards, ASTM, Philadelphia, PA, 1990. (For C, D and G-type thermocouples, microvolt to temperature equations are available and reverse equations were curve fit to the data.)

5.1 Moderate Temperature Thermocouples

5.1.1 K-Type Thermocouples (Nickel-Chromium vs. Nickel-Aluminum)

Temperature (T) to microvolt conversion for K-type T/C valid for 0 to1372 °C

$$
\begin{aligned}
V = \; & (-1.7600413686E+01) + (3.8921204975E+01* T) + (1.8558770032E-02* T^2) \\
& - (9.9457592874E-05* T^3) + (3.1840945719E-07* T^4) - (5.6072844889E-10* T^5) \\
& + (5.6075059059E-13* T^6) - (3.2020720003E-16* T^7) + (9.7151147152E-20* T^8) \\
& - (1.2104721275E-23* T^9) + (1.185976E+02*\exp(-1.183432E-04*(T-126.9686)^2))
\end{aligned}
$$

Microvolt (V) to temperature conversion for K-type T/C valid for –200 to 0 °C

$$
\begin{aligned}
T = \; & (2.5173460E-02* V) - (1.1662878E-06* V^2) - (1.0833638E-09* V^3) \\
& - (8.9773540E-13* V^4) - (3.7342377E-16* V^5) - (8.6632643E-20* V^6) \\
& - (1.0450598E-23* V^7) - (5.1920577E-28* V^8)
\end{aligned}
$$

Microvolt (V) to temperature conversion for K-type T/C valid for 0 to 500 °C

$$
\begin{aligned}
T = \; & (2.508355E-02* V) + (7.860106E-08* V^2) - (2.503131E-10* V^3) \\
& + (8.315270E-14* V^4) - (1.228034E-17* V^5) + (9.804036E-22* V^6) \\
& - (4.413030E-26* V^7) + (1.057734E-30* V^8) - (1.052755E-35* V^9)
\end{aligned}
$$

Microvolt (V) to temperature conversion for K-type T/C valid for 500 to 1372 °C

$$
\begin{aligned}
T = \; & (-1.318058E+02) + (4.830222E-02* V) - (1.646031E-06* V^2) \\
& + (5.464731E-11* V^3) - (9.650715E-16* V^4) + (8.802193E-21* V^5) \\
& - (3.110810E-26* V^6)
\end{aligned}
$$

5.1.2 J-Type Thermocouples (Iron vs. Copper-Nickel)

Temperature (T) to microvolt conversion for J-type T/C valid for –210 to 760 °C

$$V = (5.0381187815E{+}01 * T) + (3.0475836930E{-}02 * T^2) - (8.5681065720E{-}05 * T^3) + (1.3228195295E{-}07 * T^4) - (1.7052958337E{-}10 * T^5) + (2.0948090697E{-}13 * T^6) - (1.2538395336E{-}16 * T^7) + (1.5631725697E{-}20 * T^8)$$

Microvolt (V) to temperature conversion for J-type T/C valid for –210 to 0 °C

$$T = (1.9528268E{-}02 * V) - (1.2286185E{-}06 * V^2) - (1.0752178E{-}09 * V^3) - (5.9086933E{-}13 * V^4) - (1.7256713E{-}16 * V^5) - (2.8131513E{-}20 * V^6) - (2.3963370E{-}24 * V^7) - (8.3823321E{-}29 * V^8)$$

Microvolt (V) to temperature conversion for J-type T/C valid for 0 to 760 °C

$$T = (1.978425E{-}02 * V) - (2.001204E{-}07 * V^2) + (1.036969E{-}11 * V^3) - (2.549687E{-}16 * V^4) + (3.585153E{-}21 * V^5) - (5.344285E{-}26 * V^6) + (5.099890E{-}31 * V^7)$$

Microvolt (V) to temperature conversion for J-type T/C valid for 760 to 1200 °C

$$T = (-3.11358187E{+}03) + (3.00543684E{-}01 * V) - (9.94773230E{-}06 * V^2) + (1.70276630E{-}10 * V^3) - (1.43033468E{-}15 * V^4) + (4.73886084E{-}21 * V^5)$$

5.1.3 T-Type Thermocouples (Copper vs. Copper-Nickel)

Temperature (T) to microvolt conversion for T-type T/C valid for 0 to 400 °C

$$V = (3.8748106364E{+}01 * T) + (3.3292227880E{-}02 * T^2) + (2.0618243404E{-}04 * T^3) - (2.1882256846E{-}6 * T^4) + (1.0996880928E{-}8 * T^5) - (3.0815758772E{-}11 * T^6) + (4.5479135290E{-}14 * T^7) - (2.7512901673E{-}17 * T^8)$$

Microvolt (V) to temperature conversion for T-type T/C valid for –200 to 0 °C

$$T = (2.5929192E{-}02 * V) - (2.1316967E{-}07 * V^2) + (7.9018692E{-}10 * V^3) + (4.2527777E{-}13 * V^4) + (1.3304473E{-}16 * V^5) + (2.0241446E{-}20 * V^6) + (1.2668171E{-}24 * V^7)$$

Microvolt (V) to temperature conversion for T-type T/C valid for 0 to 400 °C

$$T = (2.592800E{-}02 * V) - (7.602961E{-}07 * V^2) + (4.637791E{-}11 * V^3) - (2.165394E{-}15 * V^4) + (6.048144E{-}20 * V^5) - (7.293422E{-}25 * V^6)$$

5.1.4 E-Type Thermocouples (Nickel-Chromium vs. Copper-Nickel)

Temperature (T) to microvolt conversion for E-type T/C valid for 0 to 400 °C

$$V = (5.8665508710E{+}01 * T) + (4.5032275582E{-}02 * T^2) + (2.8908407212E{-}05 * T^3) - (3.3056896652E{-}07 * T^4) + (6.5024403270E{-}10 * T^5) - (1.9197495504E{-}13 * T^6) - (1.2536600497E{-}15 * T^7) + (2.1489217569E{-}18 * T^8) - (1.4388041782E{-}21 * T^9) + (3.5960899481E{-}25 * T^{10})$$

Microvolt (V) to temperature conversion for E-type T/C valid for –200 to 0 °C

$$T = (1.6977288E{-}02 * V) - (4.3514970E{-}07 * V^2) - (1.5859697E{-}10 * V^3) - (9.2502871E{-}14 * V^4) - (2.6084314E{-}17 * V^5) - (4.1360199E{-}21 * V^6) - (3.4034030E{-}25 * V^7) - (1.1564890E{-}29 * V^8)$$

Microvolt (V) to temperature conversion for E-type T/C valid for 0 to 1000 °C

$$T = (1.7057035E{-}02 * V) - (2.3301759E{-}07 * V^2) + (6.5435585E{-}12 * V^3) - (7.3562749E{-}17 * V^4) - (1.7896001E{-}21 * V^5) + (8.4036165E{-}26 * V^6) - (1.3735879E{-}30 * V^7) + (1.0629823E{-}35 * V^8) - (3.2447087E{-}41 * V^9)$$

5.1.5 N-Type Thermocouples (Nickel-Chromium-Silicon vs. Nickel-Silicon-Magnesium)

Temperature (T) to microvolt conversion for N-type T/C valid for 0 to 1300 °C

$$V = (2.5929394601E+01 * T) + (1.5710141880E-02 * T^2) + (4.3825627237E-05 * T^3) - (2.5261169794E-07 * T^4) + (6.4311819339E-10 * T^5) - (1.0063471519E-12 * T^6) + (9.9745338992E-16 * T^7) - (6.0863245607E-19 * T^8) + (2.0849229339E-22 * T^9) - (3.0682196151E-26 * T^{10})$$

Microvolt (V) to temperature conversion for N-type T/C valid for -200 to 0 °C

$$T = (3.8436847E-02 * V) + (1.1010485E-06 * V^2) + (5.2229312E-09 * V^3) + (7.2060525E-12 * V^4) + (5.8488586E-15 * V^5) + (2.7754916E-18 * V^6) + (7.7075166E-22 * V^7) + (1.1582665E-25 * V^8) + (7.3138868E-30 * V^9)$$

Microvolt (V) to temperature conversion for N-type T/C valid for 0 to 600 °C

$$T = (3.86896E-02 * V) - (1.08267E-06 * V^2) + (4.70205E-11 * V^3) - (2.12169E-18 * V^4) - (1.17272E-19 * V^5) + (5.39280E-24 * V^6) - (7.98156E-29 * V^7)$$

Microvolt (V) to temperature conversion for N-type T/C valid for 600 to 1300 °C

$$T = (1.972485E+01) + (3.300943E-02 * V) - (3.915159E-07 * V^2) + (9.855391E-12 * V^3) - (1.274371E-16 * V^4) + (7.767022E-22 * V^5)$$

5.2 High Temperature Thermocouples

5.2.1 R-Type Thermocouples (Platinum 13%-Rhodium vs. Platinum)

Temperature (T) to microvolt conversion for R-type T/C valid for -50 to 1064 °C

$$V = (5.28961729765 * T) + (1.39166589782E\text{-}02 * T^2) - (2.38855693017E\text{-}05 * T^3) + (3.56916001063E\text{-}08 * T^4) - (4.62347666298E\text{-}11 * T^5) + (5.00777441034E\text{-}14 * T^6) - (3.73105886191E\text{-}17 * T^7) + (1.57716482367E\text{-}20 * T^8) - (2.81038625251E\text{-}24 * T^9)$$

Microvolt (V) to temperature conversion for R-type T/C valid for –50 to 250 °C

$$T = (1.8891380E\text{-}01 * V) - (9.3835290E\text{-}05 * V^2) + (1.3068619E\text{-}07 * V^3) - (2.2703580E\text{-}10 * V^4) + (3.5145659E\text{-}13 * V^5) - (3.8953900E\text{-}16 * V^6) + (2.8239471E\text{-}19 * V^7) - (1.2607281E\text{-}22 * V^8) + (3.1353611E\text{-}26 * V^9) - (3.3187769E\text{-}30 * V^{10})$$

Microvolt (V) to temperature conversion for R-type T/C valid for 250 to 1200 °C

$$T = (1.334584505E{+}01) + (1.472644573E\text{-}01 * V) - (1.844024844E\text{-}05 * V^2) + (4.031129726E\text{-}09 * V^3) - (6.249428360E\text{-}13 * V^4) + (6.468412046E\text{-}17 * V^5) - (4.458750426E\text{-}21 * V^6) + (1.994710146E\text{-}25 * V^7) - (5.313401790E\text{-}30 * V^8) + (6.481976217E\text{-}35 * V^9)$$

Microvolt (V) to temperature conversion for R-type T/C valid for 1064 to 1664 °C

$$T = (-8.199599416E{+}01) + (1.553962042E\text{-}01 * V) - (8.342197663E\text{-}06 * V^2) + (4.279433549E\text{-}10 * V^3) - (1.191577910E\text{-}14 * V^4) + (1.492290091E\text{-}19 * V^5)$$

Microvolt (V) to temperature conversion for R-type T/C valid for 1664 to 1768 °C

$$T = (3.406177836E{+}04) - (7.023729171 * V) + (5.582903813E\text{-}04 * V^2) - (1.952394635E\text{-}08 * V^3) + (2.560740231E\text{-}13 * V^4)$$

5.2.2 S-Type Thermocouples (Platinum 10%-Rhodium vs. Platinum)

Temperature (T) to microvolt conversion for S-type T/C valid for -50 to 1064 °C

$$V = (5.40313308631 * T) + (1.25934289740E-02 * T^2) - (2.32477968689E-05 * T^3) + (3.22028823036E-08 * T^4) - (3.31465196389E-11 * T^5) + (2.55744251786E-14 * T^6) - (1.25068871393E-17 * T^7) + (2.71443176145E-21 * T^8)$$

Microvolt (V) to temperature conversion for S-type T/C valid for –50 to 250 °C

$$T = (1.84949460E-01 * V) - (8.00504062E-05 * V^2) + (1.02237430E-07 * V^3) - (1.52248592E-10 * V^4) + (1.88821343E-13 * V^5) - (1.59085941E-16 * V^6) + (8.23027880E-20 * V^7) - (2.34181944E-23 * V^8) + (2.79786260E-27 * V^9)$$

Microvolt (V) to temperature conversion for S-type T/C valid for 250 to 1200 °C

$$T = (1.291507177E+01) + (1.466298863E-01 * V) - (1.534713402E-05 * V^2) + (3.145945973E-09 * V^3) - (4.163257839E-13 * V^4) + (3.187963771E-17 * V^5) - (1.291637500E-21 * V^6) + (2.183475087E-26 * V^7) - (1.447379511E-31 * V^8) + (8.211272125E-36 * V^9)$$

Microvolt (V) to temperature conversion for S-type T/C valid for 1064 to 1664.5 °C

$$T = (-8.087801117E+01) + (1.621573104E-01 * V) - (8.536869453E-06 * V^2) + (4.719686976E-10 * V^3) - (1.441693666E-14 * V^4) + (2.081618890E-19 * V^5)$$

Microvolt (V) to temperature conversion for S-type T/C valid for 1664.5 to 1768.1 °C

$$T = (5.333875126E+04) - (1.235892298E+01 * V) + (1.092657613E-03 * V^2) - (4.265693686E-08 * V^3) + (6.247205420E-13 * V^4)$$

5.2.3 B-Type Thermocouples (Platinum 30%-Rhodium vs. Platinum 6%-Rhodium)

Temperature (T) to microvolt conversion for B-type T/C valid for 0 to 630.615 °C

$$V = (-2.4650818346E{-}01 * T) + (5.9040421171E{-}03 * T^2) - (1.3257931636E{-}06 * T^3) + (1.5668291901E{-}09 * T^4) - (1.6944529240E{-}12 * T^5) + (6.2290347094E{-}16 * T^6)$$

Microvolt (V) to temperature conversion for B-type T/C valid for 22 to 250 °C

$$T = (39.464) + (3.9873 * V) - (0.13723 * V^2) + (3.3976E{-}03 * V^3) - (4.9393E{-}05 * V^4) + (4.3245E{-}07 * V^5) - (2.3105E{-}09 * V^6) + (7.3661E{-}12 * V^7) - (1.2864E{-}14 * V^8) + (9.4648E{-}18 * V^9)$$

Microvolt (V) to temperature conversion for B-type T/C valid for 250 to 700 °C

$$T = (9.8423321E{+}01) + (6.9971500E{-}01 * V) - (8.4765304E{-}04 * V^2) + (1.0052644E{-}06 * V^3) - (8.3345952E{-}10 * V^4) + (4.5508542E{-}13 * V^5) - (1.5523037E{-}16 * V^6) + (2.9886750E{-}20 * V^7) - (2.4742860E{-}24 * V^8)$$

Microvolt (V) to temperature conversion for B-type T/C valid for 700 to 1820 °C

$$T = (-2.1315071E{+}02) + (2.8510504E{-}01 * V) - (5.2742887E{-}05 * V^2) + (9.9160804E{-}09 * V^3) - (1.2965303E{-}12 * V^4) + (1.1195870E{-}16 * V^5) - (6.0625199E{-}21 * V^6) + (1.8661696E{-}25 * V^7) - (2.4878585E{-}30 * V^8)$$

5.3 Extreme Temperature Thermocouples

5.3.1 C-Type Thermocouples (Tungsten 5%-Rhenium vs. Tungsten 26%-Rhenium)

Temperature (T) to microvolt conversion for C-type T/C valid for 32 to 4200 °C

$$V = (-0.234471) + (0.7190027E\text{-}02 * T) + (0.3956443E\text{-}05 * T^2) - (0.1842722E\text{-}08 * T^3) + (0.3471851E\text{-}12 * T^4) - (0.2616792E\text{-}16 * T^5)$$

Microvolt (V) to temperature conversion for C-type T/C valid for 0 to 2315 °C

$$T = (1.53333E\text{-}01) + (7.40333E{+}01 * V) - (4.27233 * V^2) + (5.27306E\text{-}01 * V^3) - (4.73283E\text{-}02 * V^4) + (2.96511E\text{-}03 * V^5) - (1.21517E\text{-}04 * V^6) + (3.09700E\text{-}06 * V^7) - (4.44239E\text{-}08 * V^8) + (2.73989E\text{-}10 * V^9)$$

5.3.2 D-Type Thermocouples (Tungsten 3%-Rhenium vs. Tungsten 25%-Rhenium)

Temperature (T) to microvolt conversion for D-type T/C valid for 0 to 783 °C

$$V = (9.5685256E\text{-}03 * T) + (2.0592621E\text{-}05 * T^2) - (1.8464573E\text{-}08 * T^3) + (7.9498033E\text{-}12 * T^4) - (1.4240735E\text{-}15 * T^5)$$

Microvolt (V) to temperature conversion for D-type T/C valid for 0 to 783 °C

$$T = (0.52197) + (100.25 * V) - (14.579 * V^2) + (2.964 * V^3) - (0.39853 * V^4) + (3.2317E\text{-}02 * V^5) - (1.4167E\text{-}03 * V^6) + (2.5695E\text{-}05 * V^7)$$

Microvolt (V) to temperature conversion for D-type T/C valid for 783 to 2320 °C

$$T = (-2589.3) + (881.77 * V) - (108.07 * V^2) + (7.6487 * V^3) - (0.31969 * V^4) + (7.9088E\text{-}03 * V^5) - (1.0726E\text{-}04 * V^6) + (6.1624E\text{-}07 * V^7)$$

5.3.3 G-Type Thermocouples (Tungsten vs. Tungsten 26%-Rhenium)

Temperature (T) to microvolt conversion for G-type T/C valid for 0 to 2315 °C

$$V = (-1.580014E\text{-}02) + (2.883146E\text{-}04 * T) + (6.783829E\text{-}06 * T^2) - (1.795965E\text{-}09 * T^3) + (2.125270E\text{-}13 * T^4) - (1.176051E\text{-}17 * T^5)$$

Microvolt (V) to temperature conversion for G-type T/C valid for 0 to 250 °C

$$T = (0.63435) + (629.15 * V) - (2655.1 * V^2) + (10165 * V^3) - (25059 * V^4) + (38938 * V^5) - (37886 * V^6) + (22349 * V^7) - (7299.2 * V^8) + (1011.7 * V^9)$$

Microvolt (V) to temperature conversion for G-type T/C valid for 250 to 2315 °C

$$T = (85.296) + (128.76 * V) - (15.092 * V^2) + (1.8512 * V^3) - (0.15177 * V^4) + (0.0081771 * V^5) - (0.000284 * V^6) + (6.1119E\text{-}6 * V^7) - (7.4047E\text{-}8 * V^8) + (3.8619E\text{-}10 * V^9)$$

5.4 Resistance Temperature Detector (RTD) Reference Temperature

A Kaye Instruments Resistance Temperature Detector (RTD) in a Wheatstone bridge configuration is used to provide a cold-junction reference temperature for thermocouple temperature measurements. Constants obtained in calibration (A, B and C) are used in the following equation to determine temperature:

$$\text{Temperature} = A + B\left(\frac{E_O}{E_I}\right) + C\left(\frac{E_O}{E_I}\right)^2$$

where E_O is the output voltage, and E_I is the supply voltage measured across the 107 Ω bridge resistor.

Resistance Temperature Detector Equation provided by:

Resistance Temperature Detector Certificate of Calibration, Model Number RTD-20, Kaye Instruments, Bedford, MA, 1981.

6. Heat Flux

6.1 Slug Calorimeter:

This test method describes the measurement of heat transfer rate using a thermal capacitance-type calorimeter, which assumes one-dimensional heat conduction into a cylindrical piece of material (slug) with known physical properties.

Slug Calorimeter Equations provided by:
ASTM Committee E 457-96, Standard Test Method for Measuring Heat-Transfer Rate Using a Thermal Capacitance (Slug) Calorimeter, ASTM, West Conshohocken, PA, 1996.

Heat Capacity for copper provided by:
"Copper: Condensed Phase Thermochemistry Data," NIST Webbook, http://webbook.nist.gov/cgi/cbook.cgi?Name=Copper<Units=SI&cTC=on

(Based on: *Chase, M.W., Jr., NIST-JANAF Thermochemical Tables, Fourth Edition, J. Physical Chemistry Reference Data, Monograph 9, 1998, pp. 1-1951.)*

The following equations apply to copper slug calorimeters.

T = Measured temperature in Kelvin

$$t = \frac{T}{1000}$$

r = Slug radius in centimeters

m_{slug} = Slug mass in grams

$A_{slug\ face}$ = Slug heating surface area = πr^2

Cp = Heat capacity (J/mol/K)

$$= 17.72891 + (28.0987 * t) - (31.25289 * t^2) + (13.97243 * t^3) + \left(\frac{0.068611}{t^2}\right)$$

Cp converted from J/mol/K to J/g/K by dividing by Cu molecular weight = 63.55 [g / mol]

$$\text{Heat Flux } (W / cm^2) = \dot{q} = \frac{C_p \left(\frac{\Delta T}{\Delta t}\right) m_{slug}}{A_{slug\ face}}$$

6.2 Copper-Constantan Circular Foil Heat Flux ("Gardon") Gage:

This test method describes the measurement of heat flux absorbed by a thin circular foil of copper-constantan construction by convection, radiation, or a combination of both.

Copper-Constantan Circular Foil Heat-Flux Gage Equations provided by:
ASTM Committee E 511-73, Standard Test Method for Measuring Heat Flux Using a Copper-Constantan Circular Foil, Heat-Flux Gage, ASTM, West Conshohocken, PA, 1994.

K = Constant determined by manufacturer during calibration ((W / cm2) / mV)

E = Measured equilibrium thermoelectric potential between the center and edge of the foil (measured in millivolts)

Heat Flux (W / cm^2) = $\dot{q} = KE$

7. Flow Calculations

The flow calculation takes input fluid and flow meter parameters for a Venturi flow meter and outputs mass flow. The mass flow equation has been empirically derived for flow through a Venturi nozzle with pressure taps at its inlet and throat. The calculation takes accounts for different gasses, discharge coefficients, gas compressibility, and correct for errors in the system compressibility factor. The gas compressibility factor is from the Newtonian approximation of the Redlich-Kwong formula.

The Venturi discharge coefficient (Cd) and mass flow (w) are mutually dependent. Therefore, a close approximation of discharge coefficient is used to estimate mass flow and derive the Reynolds Number (R_d), with respect to diameter, from which a more accurate discharge coefficient and mass flow can be calculated.

Venturi flow equations provided by:

Bean, H.S. ed., Fluid Meters: Their Theory and Application, 6th ed., ASME, 1971.

Fluid property equations derived from:

Miller, R.W., Flow Measurement Engineering Handbook, 3rd ed., McGraw Hill, New York, 1996.

Lide, D.R., ed., CRC Handbook of Chemistry and Physics, 77th ed., CRC Press, 1996.

7.1 Venturi Flow Calculations:

P = Measured pressure (psiA)

dP = Measured differential pressure (psiD)

r = Pressure ratio = $\left(\frac{P_2}{P_1}\right)$ or $\left(1-\frac{dP}{P_1}\right)$

d = Throat diameter (in.)

D = Inlet diameter (in.)

β = Beta (d/D)

Y = System compressibility factor = $$\frac{\sqrt{\dfrac{\left(r^{\frac{2}{k}}\right)\left(\frac{k}{k-1}\right)\left(1-r^{\frac{k-1}{k}}\right)}{(1-r)\left(1-\beta^4\right)}}}{\left(1-\beta^4\right)\left(r^{\frac{2}{k}}\right)}$$

G = Specific gravity (gas dependent) = $\frac{\text{density of air}}{\text{density of gas}}$

$$E = \sqrt{\frac{1}{1-\beta^4}}$$

k = Ratio of specific heats (gas dependent)

m = Viscosity (lbm/ft/s) (gas dependent)

P_c = Critical pressure (psiA) (gas dependent)

P_r = Reduced pressure = $\frac{P}{P_c}$

T = Measured inlet temperature (R)

T_c = Critical temperature (R) (gas dependent)

T_r = Reduced temperature = $\frac{T}{T_c}$

$$A = \frac{0.42748 P_r}{(T_r)^{2.5}}$$

$$B = \frac{0.086647 P_r}{T_r}$$

$K = B^2 + B - A$

Z_o = Gas compressibility constant (gas dependent)

Z = Compressibility factor [Approximation of Redlich-Kwong compressibility factor.]

$$= Z_0 - \frac{\left(Z_0^{\ 3} - Z_0^{\ 2} - K * Z_0 - A - B\right)}{\left(3Z_0^{\ 2} - 2Z_0 - K\right)}$$

ρ = Density of an ideal gas (lbm/ft^3) = $\dfrac{2.700 * P * G}{Z * T}$

R_d = Reynolds Number, with respect to diameter = $\left(\dfrac{48}{\pi}\right)(w/d/m)$

Cd = Initial Cd = 0.99

Cd = $0.9975 - 0.00653 * \left(\dfrac{10^6}{Rd}\right)^a$ where a = 0.2 if Rd $\geq 10^6$

w = Mass flow (lbm/sec) [Assuming thermal expansion of throat is negligible.]
  = $0.52502 * Cd * Y * d^2 * E * \sqrt{\rho * dP}$

Three types of gases are used in the test facilities. Depending on which gas is used in the test procedures, a specific set of fluid properties is used.

7.1.1 Fluid Properties for Air:

G = Specific gravity = 1

P_c = Critical pressure = 543.7 psiA

T_c = Critical temperature = 238.9 R

m = Viscosity (lbm/ft/s) = 1.344E-8 $*$ T + 6.32E-6
(Based on Air Viscosity table from Miller (1996) at 1000 psiA near 60 °F.)

k = Ratio of specific heats = 1.40

Z_o = Gas compressibility constant = 0.97

7.1.2 Fluid Properties for Argon:

G = Specific gravity = 1.3789

P_c = Critical pressure = 706.9 psiA

T_c = Critical temperature = 271.4 R

m = Viscosity (lbm/ft/s) = 1.68E-8 $*$ T + 8.20E-6
(Based on Argon Viscosity table from Miller (1996) at 1450 psiA near 60 °F.)

k = Ratio of specific heats = 1.667

Z_o = Gas compressibility constant = 0.95

7.1.3 Fluid Properties for Nitrogen:

G = Specific gravity = 0.9672

P_c = Critical pressure = 492.3 psiA

T_c = Critical temperature = 227.2 R

m = Viscosity (lbm/ft/s) = $3.440E{-}11 * T^2 - 2.387E{-}8 * T + 1.647E{-}5$
(Based on Nitrogen Viscosity table from Miller (1996) at 1000 psiA near 60 °F.)

k = Ratio of specific heats = 1.40

Z_o = Gas compressibility constant = 0.98