THERMAL MODELLING AND OPTIMISATION OF A HIGH TEMPERATURE BLACKBODY RADIATOR

by

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CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledge within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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ABSTRACT

Blackbody radiators, or graphite tube furnaces, are commonly used in the calibration of pyrometers for temperature range up to 3 000 °C. These radiators are usually constructed from graphite cylindrical shaped cavities insulated by graphite felt or similar materials. The calibration uncertainties associated with one of these radiators, a 48 kW Thermogage furnace, are 1 °C at 1 000 °C and a wavelength of 650 nm rising to 2 °C at 2 000 °C. These uncertainties are mainly due to deviations of the blackbody emissivity from 100%. The emissivity has been calculated to be 99.2% at a temperature of 1 000 °C and a wavelength of 650 nm, increasing to 99.9% in some cases.

To improve this Thermogage furnace's temperature calibration uncertainty to the level required, the emissivity must be increased to 99.9% over the full temperature range. This can be achieved by improving the temperature uniformity of its cavity inner walls. Therefore, the aim of this work is to achieve this emissivity increase by optimising the temperature uniformity of the blackbody furnace graphite tube.

A quasi 2-D numerical model has been developed to predict the temperature profile of the Thermogage furnace's tube. This has been used to optimise the temperature uniformity based on input parameters such as the thermophysical properties of ATJ graphite and WDF graphite felt. These thermophysical properties have been thoroughly investigated and implemented into the quasi 2-D numerical model.

The numerical predictions generated have been validated by comparing them to the measured temperature profile and radial heat fluxes of the graphite tube. Once an agreement has been achieved between the measured and the modelled results, the quasi 2-D numerical model has been used to generate numerical predictions of the temperature profile based on design methodologies that include changing the cross sectional area and the length of the graphite tube as well as using different insulating gases.

With a new tube design, a better temperature uniformity has been achieved and thus improvement in the cavity emissivity resulting into temperature uncertainty of better than 0.02 °C for operating temperatures from 1 000 to 1 600 °C and at a wavelength of 650 nm.

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NOMENCLATURE

Roman Symbols		First Occurrence
a	Radius of an electrical wire	72
A	Area of the blackbody cavity hole	11
	Area of a disk	77
A_{A4}	Area of an A4 sized paper	194
A_{amb}	Area of the ATJ graphite tube's opening to the ambient	77
A_c	Cross sectional area	98
$A_{contact}$	Fibre-to-fibre contact area	34
A_{felt}	Area of a piece of a WDF graphite felt	194
A_g	Cross sectional area of a gap between two surfaces	123
A_i	Area at node *i*	87
A_j	Area at node *j*	87
A_{septum}	Area of the ATJ graphite tube's middle septum	77
A_{ring}	Surface area of a ring inside the ATJ graphite tube	98
A_{Silica}	Cross sectional area of the silica tube	124
A_{TC}	Cross sectional area of the Pt/Pt-Rh thermocouple wires	70
A_{WJ}	Cross sectional of the water jacket	127
c_0	Speed of light in vacuum	2
	Polynomial coefficient	32
c_1	Polynomial coefficient	32
c_2, c_3, c_4, c_5	Polynomial coefficients or used as constants	32
C	Constant used in the measurement of the thermal conductivity of WDF graphite felt	40
C_1	First radiation constant	3
C_2	Second radiation constant	3
C_{fr}	Experimentally determined radiation constant	39
c_I	Sinusoidal current sensitivity factor	110
$c_{k_{ATJ}}$	ATJ graphite thermal conductivity sensitivity factor	111
c_{M_i}	Radiant exitance at node *i* sensitivity factor	89
c_{M_j}	Radiant exitance at node *j* sensitivity factor	89
c_{M_w}	Middle septum radiant exitance sensitivity factor	89

C_p	Specific heat of ATJ graphite	55
$C_{p_{water}}$	Specific heat of water	99
c_V	Sinusoidal voltage sensitivity current	110
$c_{V_{water}}$	Water flowrate sensitivity factor	112
$c_{\partial T/\partial x}$	Temperature gradient sensitivity factor	111
$c_{\Delta T_{water}}$	Water coolant temperature change sensitivity factor	112
$c_{\varepsilon_{ATJ}}$	ATJ graphite emissivity sensitivity factor	89
d	Depth of the blackbody cavity	11
	Depth of a 360° cut	166
D	Distance between two electrical wires' centres	72
D_{Silica}	Diameter of the silica tube	126
D_{WJ}	Diameter of the water jacket	126
d_v	Distance between voltage measurement contact points	40
E	Energy	85
E_i	Total irradiance from other surfaces onto node i	87
$E_{\lambda,b}$	Spectral hemispherical power	3
f	Volume fraction of graphite felt bulk material	30
F	Bankvall geometrical factor	38
	View or configuration factor	76
F_{as}	View/configuration factor: ambient to the surface area of the Pt/Pt-Rh thermocouple wire	133
f_{exact}	Numerical model exact solution	80
F_{ia}	View/configuration factor: node *i* to the ambient	98
F_{ji}	View/configuration factor: node *j* to node *i*	87
F_{js}	View/configuration factor: ring element (*j*) to the middle septum of the graphite tube	133
F_{sa}	View/configuration factor: middle septum to ambient	98
F_{si}	View/Configuration factor: ring element (*i*) to the middle septum of the graphite tube	133
F_{ss}	View/configuration factor: ATJ graphite tube's middle septum to the surface area of the Pt/Pt-Rh thermocouple wire	77
F_{xx}	View/configuration factor for parallel circular disks with centres along the same normal	77
F_{wi}	View/configuration factor: ATJ graphite middle septum to node *i*	87

g	Gravitation acceleration	31
	Gap between two electrical wires	72
	Gap between two surfaces	123
G_F	Effective thermal conductivity of graphite felt	82
G_s	Surface Conductance between Pt/Pt-Rh thermocouple wire and the surface of ATJ graphite tube	70
$G_{s,cond}$	Surface conductance due to conduction	71
$G_{s,rad}$	Surface conductance due to radiation	71
g_{WJ}	Distance between the silica tube and the water jacket	126
h	Universal Planck constant	2
	Node width	135
H	Strong *et al*'s geometrical factor	38
i	Node count	63
I	Electrical current	120
I_{RMS}	Root mean square of the sinusoidal electrical current	97
$I_{\lambda,b}$	Spectral radiance or total intensity.	2
j	Node count	63
k	Boltzmann universal constant	2
	Thermal conductivity	39
	Coverage factor	130
k_1	Thermal conductivity of air	29
k_2	Thermal conductivity of fibre	29
k_{across}	Thermal conductivity in the "across-the-grain" direction	61
k_{ATJ}	Thermal conductivity of ATJ graphite	62
$k_{average}$	Average thermal conductivity	61
k_{eff}	Effective thermal conductivity	126
k_f	Thermal conductivity of graphite felt	30
k_{fc}	Thermal conductivity due to free convection	29
k_{Felt}	Thermal conductivity of felt (constant)	82
k_{fr}	Thermal conductivity due to radiative exchanges between fibres	30
k_{gas}	Thermal conductivity of a gas	72
k_{gc}	Thermal conductivity due to gas conduction	30
k_{gr}	Thermal conductivity due to gas radiation	30
k_{ISF}	Thermal conductivity of imperfectly stratified felt	33
k_m	Thermal conductivity of textile fibres	29

k_{PSF}	Thermal conductivity of a perfectly stratified felt	34
k_s	Thermal conductivity of the graphite bulk material	33
k_{sc}	Thermal conductivity due to solid conduction along the graphite fibres	30
k_{Silica}	Thermal conductivity of silica	124
k_{TC}	Thermal conductivity of the Pt/Pt-Rh thermocouple wires	70
k_{with}	Thermal conductivity in the "with-the-grain" direction	61
L	Height of a small cavity	31
	Length of the ATJ graphite tube	68
l_f	Free mean path for molecule-fibre collision	31
l_{fibre}	Length of fibre equal to one-half the distance between successive fire junctions	34
m	Number of nodes	98
M_i	Radiant exitance measured by the pyrometer	87
M_j	Radiant exitance from rings inside the ATJ graphite tube	87
$M_{p(T),i}$	Radiant exitance due to surface temperature	87
M_w	Middle septum radiant exitance	87
n	Number of nodes	87
n_{fibre}	Number of fibre-to-fibre contacts	34
P	Power per unit length	40
$P_{conduction}$	Heat transfer rate by conduction along the ATJ graphite tube	97
$P_{electrical}$	Heat transfer rate generated electrically	97
Pr	Prandtl number	126
P_{radial}	Heat transfer rate in the radial direction	97
$P_{radiation}$	Heat transfer rate by radiation to ambient	97
p_{TC}	Perimeter of the Pt/Pt-Rh thermocouple wire	70
q_{ai}	Radiative heat flux between environment to node *i*	132
q_{amb}	Heat flux (radiative) between the Pt/Pt-Rh thermocouple and the ambient	77
q_{as}	Radiative heat flux between the environment and middle septum	132
q_{cond}	Heat flux by conduction	129
q_e	Electrical power	120
$q_{e,cc}$.	Electrical power generated internally by CC material	72
q_{ji}	Heat flux from node *j* to node *i*	132

q_{js}	Radiative heat flux between node *j* and the middle septum	132
$q_{L,cond}$	Heat flux to the left of the node	119
$q_{R,cond}$	Heat flux to the right of the node	119
q_{rad}	Heat flux by radiation	119
$q_{rad,i}$	Heat flux by radiation at node *i*	119
$q_{rad,s}$	Heat flux by radiation at the middle septum	132
q_{radial}	Heat flux in the radial direction	120
q_s	Heat flux (radiative) between the Pt/Pt-Rh thermocouple and the ATJ graphite tube surface	77
q_{septum}	Heat flux (radiative) between the Pt/Pt-Rh thermocouple and the ATJ graphite tube's middle septum	77
q_{si}	Heat flux between the middle septum and node *i*	132
q_{st}	Internally stored energy	120
$q'_{WJ,Conv}$	Heat flux per unit length due to convection	126
$q'_{WJ,Rad}$	Heat flux per unit length due to radiation	126
$q'_{WJ,Total}$	Total heat flux per unit length	126
r	Radius of a graphite fibre.	31
r_1, r_2	Radii of graphite felt	124
R_1, R_2	View factor variables	77
Ra_c^*	Modified Rayleigh number	126
Ra_L	Rayleigh number per unit length	31
R_{amb}	Thermal resistance due to radiative exchanges between the Pt/Pt-Rh thermocouple and the ambient	77
R_{ATJ}	Thermal resistance of an ATJ graphite node	120
R_{cc}	Carbon composite thermal resistance	129
R_{Cond}	Thermal resistance due to conduction	123
R_e	Electrical resistance of a node	64
R_{elec}	Leakage electrical resistance	72
R_{Felt}	Thermal resistance of graphite felt	123
$R_{Felt/Foils}$	Thermal resistance between graphite felt and foils	123
R_{Foils}	Thermal resistance of graphite foils	122
$R_{Foils/Silica}$	Thermal resistance between graphite foils and silica	122
R_{Rad}	Thermal resistance due to radiation	123

R_{radial}	Thermal resistance of graphite felt in the radial direction	120
R_s	Thermal resistance due to radiation exchanges between the Pt/Pt-Rh thermocouple wire and the surface of the ATJ graphite tube	77
$R_{s,cond}$	Thermal resistance due to surface to surface conduction	72
$R_{s,rad}$	Thermal resistance due to surface to surface radiation	93
R_{septum}	Thermal resistance due to radiative exchanges between the Pt/Pt-Rh thermocouple and the middle septum	77
R_{Silica}	Thermal resistance of silica	122
R_{TC}	Thermal resistance of the Pt/Pt-Rh thermocouple	93
R_{WJ}	Thermal resistance of the water jacket	122
t	Time	39
t_{felt}	Thickness of WDF graphite felt	194
T	Absolute temperature	2
T_{amb}	Absolute ambient temperature	77
T_{ave}	Average absolute temperature of ATJ graphite	98
T_{end}	Absolute temperature of the graphite tube ends	68
T_o	Temperature of the outside of the ATJ graphite tube	203
$T_{Pt/Pt\text{-}Rh}$	Absolute temperature of the Pt/Pt-Rh thermocouple wires	99
T_s	Absolute temperature of the graphite tube surface	68
T_{septum}	Absolute temperature of the ATJ graphite tube's middle septum	77
T_{Silica}	Absolute temperature of the silica	126
T_{TC}	Absolute temperature of the thermocouple	69
T_{water}	Absolute temperature of water coolant	99
T_{WJ}	Absolute temperature of the water jacket	126
u_{cal}	Thermocouple calibration standard uncertainty	80
u_I	Sinusoidal current standard uncertainty	110
$u_{k_{ATJ}}$	ATJ graphite thermal conductivity uncertainty	111
u_{M_i}	Radiant exitance standard uncertainty	89
u_{M_j}	Rings radiant exitance standard uncertainty	89
u_{M_w}	Middle septum radiant exitance standard uncertainty	89
$u_{M_{P(T),i}}$	Total radiant exitance standard uncertainty	89

u_{out}	Output heat transfer rate standard uncertainty	112
$u_{P_{conduction}}$	Conduction heat transfer rate standard uncertainty	111
$u_{P_{electrical}}$	Electrically generated heat flux standard uncertainty	110
u_{pos}	Thermocouple positioning standard uncertainty	81
$u_{P_{radial}}$	Radial heat transfer rate standard uncertainty	112
$u_{s,rad}$	Radiative contact resistance standard uncertainty	81
u_T	Temperature measurement standard uncertainty	81
u_V	Sinusoidal voltage standard uncertainty	110
$u_{V_{water}}$	Water flowrate standard uncertainty	112
$u_{\delta T/\delta x}$	Temperature gradient standard uncertainty	111
$u_{\Delta T_{water}}$	Water coolant temperature change standard uncertainty	112
$u_{\varepsilon_{ATJ}}$	ATJ graphite emissivity standard uncertainty	89
V_o	Constant voltage used in optical calibration	84
V_{cc}	Voltage across the CC material	130
V_{felt}	Volume of a piece of WDF graphite felt	194
V_{in}	Voltage measured across the ATJ graphite tube	97
V_m	Optical detector voltage signal	84
V_{out}	Voltage measured at across the copper electrodes	97
V_{RMS}	Root mean square of the sinusoidal voltage	97
V_{water}	Flowrate of water (Brass water jacket)	99
w	Width of a 360° cut	166
w_{A4}	Weight of an A4 sized paper	194
w_{cut}	Weight of a cut piece of an A4 sized paper	194
w_{felt}	Weight of a WDF graphite felt	194
x	Axial coordinate Distance between two disks	63 78
x_{ia}	Distance between ring (i) and the opening at the end of the AJT graphite tube	197
x_{sa}	Distance between the middle septum and the opening at the end of the AJT graphite tube	197
X	View factor variable	78
X_F	View factor variable	133

X_i	View factor variable	88
X_{ia}	View factor variable	197
X_r	View factor variable	88
X_s	View factor variable	88
X_{sa}	View factor variable	197

Greek Symbols

α	Ratio of graphite fibre radius to contact spot radius	35
α_g	Thermal diffusivity of air	31
α_f	Experimentally determined opacity factor ($1/\alpha_f^2$)	38
α_N	Stability requirement constant	139
β	Scattering function	38
β_g	Volumetric thermal expansion coefficient of air	31
Δ	Difference	6
ε	Emissivity of a surface	5
ε_1	Emissivity of surface 1	123
ε_2	Emissivity of surface 2	123
ε_{amb}	Emissivity of the ambient	76
ε_{ATJ}	Emissivity of ATJ graphite	87
ε_{BB}	Emissivity of a blackbody cavity	11
ε_{eff}	Effective emissivity of the 48kW Thermogage furnace's cavity	178
ε_g	Emissivity of graphite	72
ε_{Pt}	Emissivity of platinum	72
$\varepsilon_{s,eff}$	Effective emissivity between two surfaces	123
ε_{Silica}	Emissivity of the silica tube	127
$\varepsilon_{r,eff}$	Effective emissivity between two surfaces	72
ε_{surf}	Emissivity of the material constituting a blackbody cavity	11
ε_{WJ}	Emissivity of the water jacket	127
θ	Phase angle	97
κ	Electrical resistivity	94
λ	Wavelength	2

μ_{TC}	Defined constant by Carslaw & Jaeger (1959)	69
ν_g	Kinematic viscosity of air	31
v_1	Volume fraction of air	29
v_2	Volume fraction of fibre	29
ξ_{cond}	Distance offset – solution to the transmission line matrix	96
π	Pi	3
ρ_{ATJ}	Density of ATJ grade graphite	64
ρ_{felt}	Density of WDF graphite felt	194
$\rho_{water_{15^\circ C}}$	Density of water at 15 °C	99
σ	Stefan-Boltzmann constant	38
σ_a	Absorption coefficient	38
σ_e	Extinction coefficient	38
σ_s	Diffusion coefficient	38
τ	Graphite fibre tortuosity	35
χ	Attenuation	98
υ_f	Frequency of graphite fibre crossing from one layer to another	35
ς	Schuhmeister first constant	29
ψ	Schuhmeister second constant	29
ω_{ATJ}	Electrical resistivity of ATJ graphite	58

Subscripts

amb	Ambient
ATJ	ATJ grade graphite
BB	Ideal blackbody surface
PSF	Perfectly stratified felt
rad	Radiation
radial	Radial direction
Real	Real blackbody surface
WJ	Water Jacket

Abbreviations

1-D	1-dimensional

2-D	2-dimensional
3-D	Three-dimensional
AC	Alternating current
AGA	Graphite material grade
AGOT	Graphite material grade
AGSR	Graphite material grade
AGSX	Graphite material grade
Ar	Argon gas
ATJ	Graphite material grade
ATL	Graphite material grade
CC	Carbon-composite
EXCEL	Microsoft EXCEL program
He	Helium gas
IKE	Institut für Kernenergetik, Universität Stuttgart
MTSP	Medium temperature standard pyrometer
N_2	Nitrogen gas
NMIA	National Measurement Institute, Australia
NMIJ	National Measurement Institute of Japan
USA	United States of America
VNIIOFI	All-Russian Research Institute for Optical and Physical Measurements
WDF	Graphite felt grade