NATIONAL PHYSICAL LABORATORY
Teddington Middlesex UK TW11 0LW Telephone +44 20 8977 3222

Test Report

UKAS
TESTING
0002

Calculations of the thickness of five types of insulation product required to reduce the heat loss or heat gain from specified applications by 90%.

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29 JAN 2016

FOR

TIMSA
Kingsley House, Ganders Business Park,
Kingsley, Bordon, Hampshire
GU35 9LU

For the attention of Lauren Fairley

IDENTIFICATION

NPL Quote numbers:	2015100035.
TIMSA PO	TIMSA 2015

OBJECTIVE

To calculate:
a) The thickness of three types "insulating coatings" and one traditional glass wool insulation required to reduce the heat loss of a simple heated system, held at 180°C by 90%.

b) The thickness of three types "insulating coatings" and one traditional PUR insulation required to reduce the heat gain of a simple cooled system, held at 10°C by 90%.

Date of issue 20 January 2016 Signed R. Williams (Authorised signatory)

Checked by: J.W. Name: R. WILLIAMS. for Managing Director

Details of the systems used for the comparisons

1) The overall assumptions of the calculation methodology are shown in Figure 1

2) The process container comprises a vertical, 5 mm thick, 2 metres high steel plate

3) The heat loss and heat gain calculations were carried firstly without any insulation and then insulated with the products specified in Table 1.

4) The internal surface temperature of this container was assumed to be the specified process temperatures – that is, the internal heat transfer processes were ignored.

5) The system has been assumed to be standing in still air at 20 °C for the heat loss situations and in still air at 25 °C in the heat gain situations – so natural convection processes have been assumed.

6) The surroundings are assumed to be much larger than the system under investigation and so the surrounding area has been approximated to a blackbody.

7) The temperature of the surroundings have been assumed to be the same as the ambient air temperature – that is 20 °C and 25 °C as appropriate.

8) The system is indoors - there is NO solar gain component.

9) The calculations were carried out under 1D steady-state conditions.

10) Both convective and radiative heat loss & gain have been included in the calculations.

11) All the systems have been assumed to have an external emissivity of 0.9 except for product "A" which has an emissivity of 0.85.

12) The convective and radiant heat transfer coefficients were calculated from the system parameters, not simply taken from tabulated values.

13) The comparisons made are:
    a) Heat loss situation: Between stone wool slab – 100kg/m^3 and systems A, B and C when the process temperature is 180 °C with an ambient air temperature of 20 °C.
    b) Heat gain situation: Between polyurethane / polyisocyanurate – 35kg/m^3 (aged) and systems A, B and C when the process temperature is 10 °C with an ambient air temperature of 25 °C.

14) In each case, the insulation thickness required to reduce the heat loss or heat gain to 10% of the uninsulated heat loss or heat gain has been calculated.

Checked by: J. W.

Properties of the insulation systems being compared are given in Table 1

Table 1 Product data

Product name	Product type	Density	λ W/m.K	Emissivity
A	"Insulating coating"	0.623 kg/litre	0.0698	0.85
B	"Insulating coating"	0.56 kg/litre	0.085	0.9 [1]
C	"Insulating coating" containing Aerogel	0.5 to 0.9 g/cm^3	0.045	0.9 [1]
Stone wool slab – 100kg/m^3	Stone wool slab.	100 kg/m^3	equation [2]	0.9 [1]
polyurethane / polyisocyanurate – 35kg/m^3	Rigid Polyurethane / polyisocyanurate	35 kg/m^3	0.026	0.9 [1]

Note [1] These values have been assumed
Note [2] Equation $\lambda = 0.0000006T^2 - 0.0000082T + 0.0417839$
Where λ = thermal conductivity (W/m.K)
T = mean temperature (°C)

Description of the calculation methodology
The method used was an iterative procedure carried out manually using an EXCEL Spreadsheet. Screen shots of the one of these spreadsheet calculations are shown in Figures 2 and 3.

The Convective Heat Transfer Coefficient (h_c) was calculated from the Nusselt Number, the thermal conductivity of air and the height of the container surface. The Nusselt Number was calculated from either Equation 1 or 2 [1] using the Raleigh Number as the criteria. All the air properties were calculated at the mean air temperature which is the mean of the system surface temperature and the ambient air temperature.

$$Nu_m = 0.68 + \frac{0.67\, Ra_L^{1/4}}{\left[1+(0.492/Pr)^{9/16}\right]^{4/9}} \qquad For\ 10^{-1} < Ra_L < 10^{9} \quad \text{.... Equation 1}$$

$$Nu_m^{1/2} = 0.825 + \frac{0.387\, Ra_L^{1/6}}{\left[1+(0.492/Pr)^{9/16}\right]^{8/27}} \qquad For\ 10^{-1} < Ra_L < 10^{12} \quad \text{.... Equation 2}$$

Where Nu_m = Mean Nusselt Number
Pr = $Prandtl\ Number$
Ra = $Rayleigh\ Number$

The Radiation Heat Transfer Coefficient was calculated using Equation 3.

$$h_r = \sigma.\epsilon.F.(T_1^4 - T_2^4)/(T_1 - T_2) \qquad \text{..... Equation 3}$$

Where
σ $= Stefan - Boltzmann\ constant$
ε $= emittance\ of\ the\ surface$
F $= View\ factor\ (assumed\ to\ be\ 1)$
A $= Area$
T_1 $= Temperature\ of\ system\ outer\ surface$ (K)
T_2 $= Temperature\ of\ surroundings\ (K)$

The calculation procedure is based on the fact that the heat transferred through the insulation will be equal to the heat lost or gained from the surface by convection and radiation (see equation 4).

$$Q = A\lambda_s \frac{(T_0 - T_3)}{L_s} = A\lambda_i \frac{T_3 - T_1}{L_i} = Ah_c\,(T_1 - T_2) + A\,h_r(T_1 - T_2) \qquad \text{.........Equation 4}$$

Where:
$Q -\ heat\ flow\ rate\ \ W$
$\lambda_s - Thermal\ conductivity\ of\ steel\ W/(m.K)$
$\lambda_i -\ Thermal\ conductivity\ of\ insulation\ W/(m.K)$
$h_c -\ Convective\ heat\ tranfer\ coefficient\ W/(m^2.K)$
$h_r -\ Radiation\ heat\ transfer\ coefficient\ W/(m^2.K)$
$T_0 - Process\ temperature$ (°C)
$T_3 - Process\ container\ or\ interface\ between\ steel\ \&\ insulation\ temperature$ (°C)
$L_s - Container\ wall\ thickness\ (m)$
$L_i - Insulation\ thickness\ (m)$

Because λ_s, λ_i, h_c, h_r are temperature dependent properties there is a need to calculate the interface and surface temperatures to be able to evaluate them at the appropriate temperature. A spreadsheet was therefore set up to calculate all the relevant properties from the input data. The external surface temperature of the process container (insulated or uninsulated) and the thickness of the insulation are input manually. The iterative calculation procedure is then carried out as follows (one of the heat loss situations is shown in Figures 2 and 3 for illustration purposes):

Calculation procedure for the uninsulated situations

1) For the uninsulated situation the thickness of the insulation is set to zero

2) Input an estimated value for the surface temperature of the process container

3) The spreadsheet uses that value to calculate all the relevant properties and then calculates the surface and interface temperatures based on that estimated value.

4) The manually entered surface temperature estimate is then changed until the estimated value and the calculated value are the same.

5) That value now gives the correct density of heat flow rate (W/m^2) through the process container wall.

6) Calculate 10% of that density of heat flow rate. This is the target value when insulated.

Calculation procedures for the insulated situations

1) For the insulated situation the thickness of the insulation is estimated and manually input.
2) Input an estimated value for the surface temperature of the process container
3) The spreadsheet uses those values to calculate all the relevant properties and then calculates the surface temperature and the density of heat flow rate based on those estimated values.
4) The manually entered estimated insulation thickness is then changed until the density of heat flow rate equals the target value.
5) The manually entered surface temperature estimate is then changed until the estimated value and the calculated value are the same.
6) Steps 4 and 5 have to be repeated as each value effects the other.
7) The insulation thickness value now gives the correct density of heat flow rate (W/m^2) through the process container wall which now equals the target value

Calculation results

a) Process temperature Environment temperature situation	b) c) Heat LOSS	HEAT LOSS		Thermal conductivity of steel & insulations (W/m.K)	Surface temperature of steel or insulation (°C)	Temperature drop across the steel or insulation (°C)
Process temperature		180	°C			
Environmental air temperature		20	°C			
Heat loss rate from uninsulated steel vessel		2858.2	W/m^2	50	179.71	159.71
Heat loss rate from steel vessel after reduction of 90%		285.82	W/m^2			
Thickness of stone wool slab – 100kg/m³ to reduce heat loss rate by 90%		22.4	mm	0.0487	48.21	131.79
Thickness of Product A to reduce heat loss rate by 90%		32.0	mm	0.0698	48.99	131.01
Thickness of Product B to reduce heat loss rate by 90%		39.2	mm	0.0850	48.21	131.79
Thickness of Product C to reduce heat loss rate by 90%		20.7	mm	0.0450	48.20	131.80

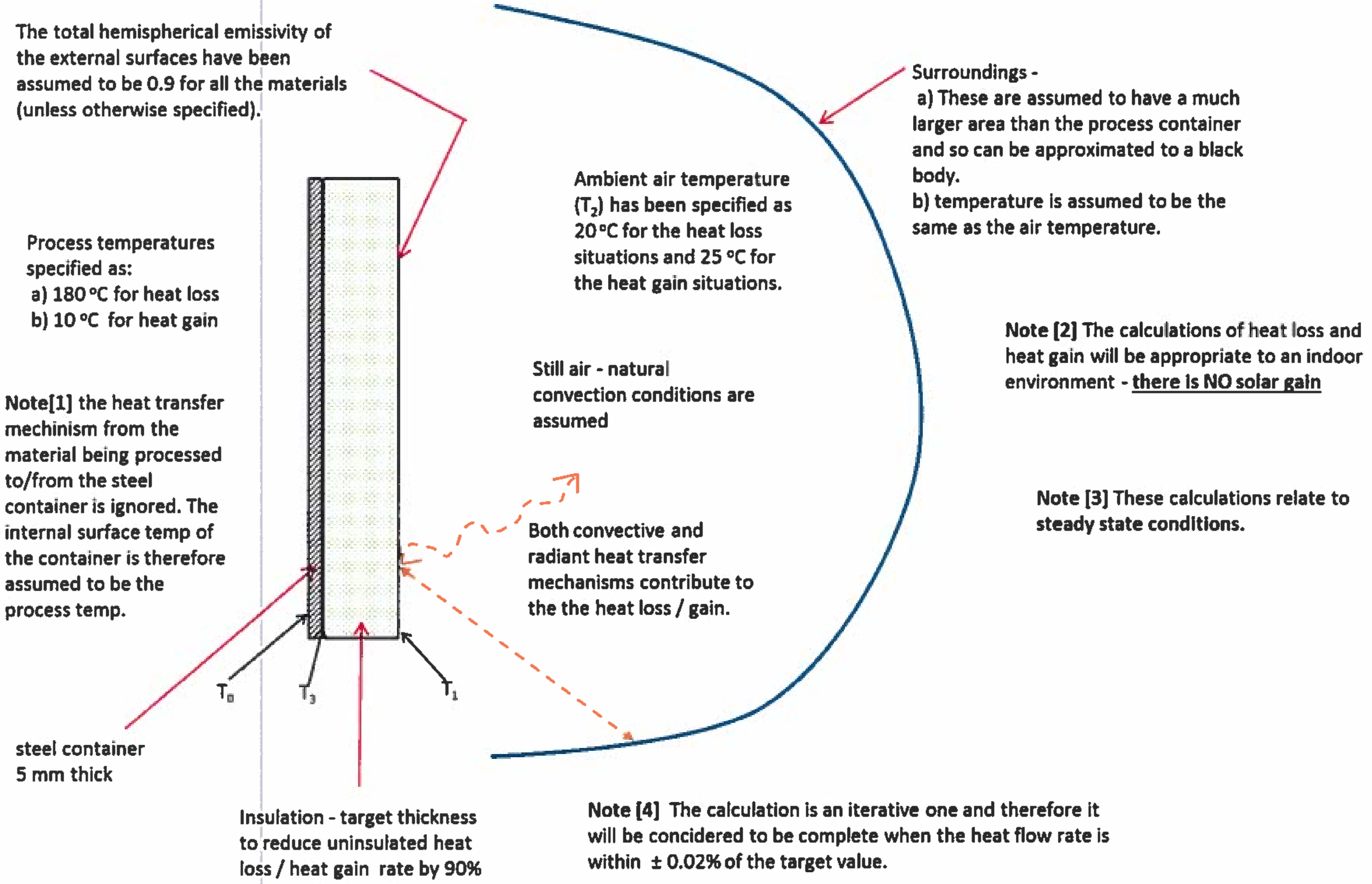
a) Process temperature Environment temperature situation	b) c) Heat GAIN	HEAT GAIN		Thermal conductivity of steel & insulations (W/m.K)	Surface temperature of steel or insulation (°C)	Temperature drop across the steel or insulation (°C)
Process temperature		10	°C			
Environmental air temperature		25	°C			
Heat gain rate from uninsulated steel vessel		-128.03	W/m^2	50	10.01	-0.01
Heat loss rate from steel vessel after reduction of 90%		-12.80	W/m^2			
Thickness of polyurethane / polyisocyanurate – 35kg/m³ to reduce heat gain by 90%		26.8	mm	0.0260	23.22	-13.22
Thickness of Product A to reduce heat gain rate by 90%		71.7	mm	0.0698	23.15	-13.15
Thickness of Product B to reduce heat gain rate by 90%		87.8	mm	0.0850	23.22	-13.22
Thickness of Product C to reduce heat gain rate by 90%		46.5	mm	0.0450	23.22	-13.22

References

[1] Churchill, S. W. and H. H. S. Chu: "Correlating equations for laminar and turbulent free convection from a vertical plate

Checked by: J.W. GTB

Figure 1 Overall assumptions of the calculation methodology



The total hemispherical emissivity of the external surfaces have been assumed to be 0.9 for all the materials (unless otherwise specified).

Process temperatures specified as:
a) 180 °C for heat loss
b) 10 °C for heat gain

Note[1] the heat transfer mechinism from the material being processed to/from the steel container is ignored. The internal surface temp of the container is therefore assumed to be the process temp.

steel container
5 mm thick

Insulation - target thickness to reduce uninsulated heat loss / heat gain rate by 90%

Ambient air temperature (T_2) has been specified as 20 °C for the heat loss situations and 25 °C for the heat gain situations.

Still air - natural convection conditions are assumed

Both convective and radiant heat transfer mechanisms contribute to the the heat loss / gain.

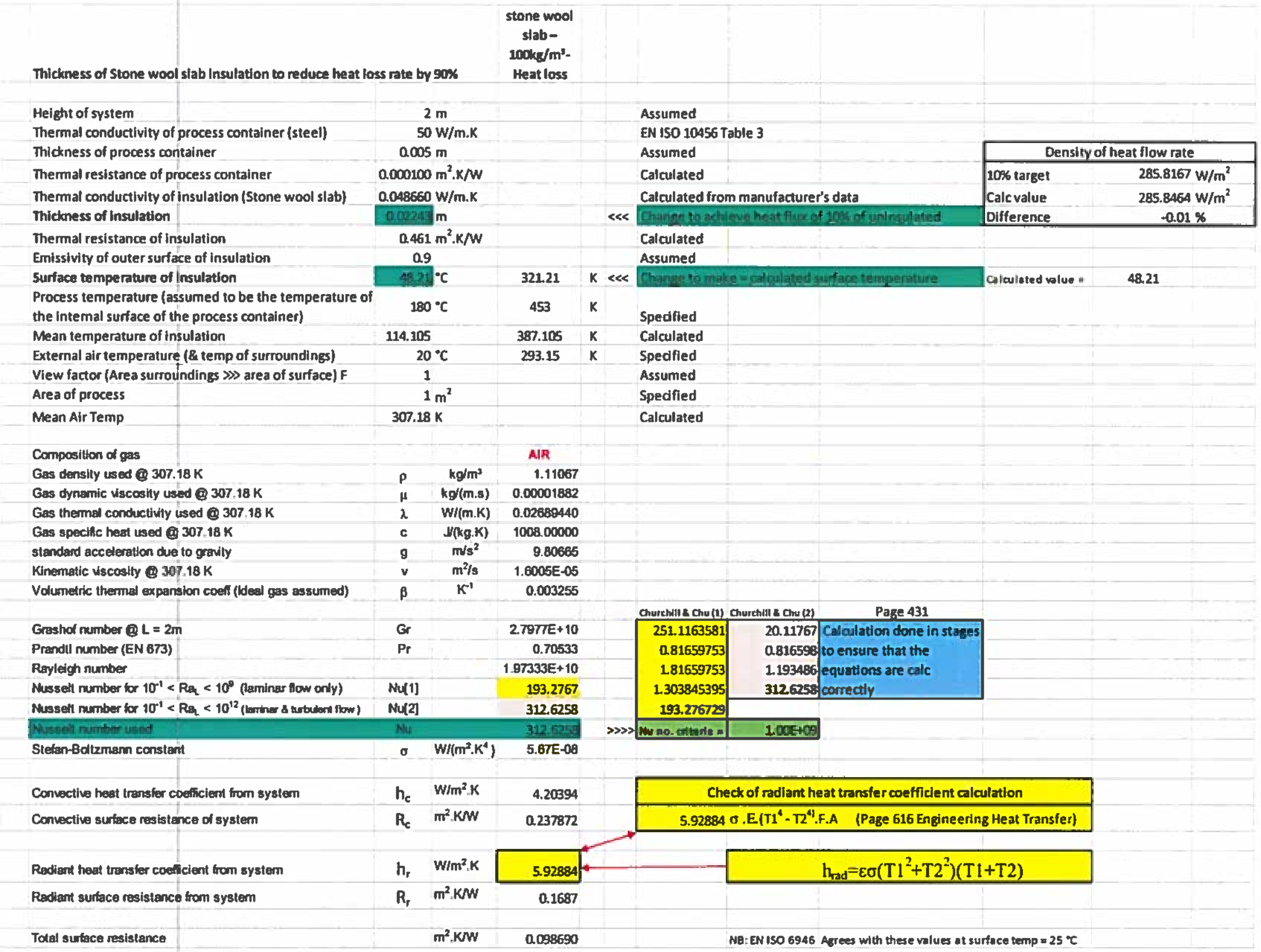
Surroundings -
a) These are assumed to have a much larger area than the process container and so can be approximated to a black body.
b) temperature is assumed to be the same as the air temperature.

Note [2] The calculations of heat loss and heat gain will be appropriate to an indoor environment - there is NO solar gain

Note [3] These calculations relate to steady state conditions.

Note [4] The calculation is an iterative one and therefore it will be concidered to be complete when the heat flow rate is within ± 0.02% of the target value.

Figure 2 The spreadsheet calculation method – Part 1



Thickness of Stone wool slab insulation to reduce heat loss rate by 90%				stone wool slab – 100kg/m³ - Heat loss					
Height of system	2 m						Assumed		
Thermal conductivity of process container (steel)	50 W/m.K						EN ISO 10456 Table 3		
Thickness of process container	0.005 m						Assumed	Density of heat flow rate	
Thermal resistance of process container	0.000100 m^2.K/W						Calculated	10% target	285.8167 W/m^2
Thermal conductivity of insulation (Stone wool slab)	0.048660 W/m.K						Calculated from manufacturer's data	Calc value	285.8464 W/m^2
Thickness of insulation	0.02243 m					<<<	Change to achieve heat flux of 10% of uninsulated	Difference	-0.01 %
Thermal resistance of insulation	0.461 m^2.K/W						Calculated		
Emissivity of outer surface of insulation	0.9						Assumed		
Surface temperature of insulation	48.21 °C			321.21	K	<<<	Change to make = calculated surface temperature	Calculated value =	48.21
Process temperature (assumed to be the temperature of the internal surface of the process container)	180 °C			453	K		Specified		
Mean temperature of insulation	114.105			387.105	K		Calculated		
External air temperature (& temp of surroundings)	20 °C			293.15	K		Specified		
View factor (Area surroundings >>> area of surface) F	1						Assumed		
Area of process	1 m^2						Specified		
Mean Air Temp	307.18 K						Calculated		
Composition of gas				AIR					
Gas density used @ 307.18 K		ρ	kg/m³	1.11067					
Gas dynamic viscosity used @ 307.18 K		μ	kg/(m.s)	0.00001882					
Gas thermal conductivity used @ 307.18 K		λ	W/(m.K)	0.02689440					
Gas specific heat used @ 307.18 K		c	J/(kg.K)	1008.00000					
standard acceleration due to gravity		g	m/s^2	9.80665					
Kinematic viscosity @ 307.18 K		v	m^2/s	1.6005E-05					
Volumetric thermal expansion coeff (ideal gas assumed)		β	K^{-1}	0.003255					
Grashof number @ L = 2m		Gr		2.7977E+10					
Prandtl number (EN 673)		Pr		0.70533					
Rayleigh number				1.97333E+10					
Nusselt number for $10^{-1} < Ra_L < 10^9$ (laminar flow only)		Nu[1]		193.2767					
Nusselt number for $10^{-1} < Ra_L < 10^{12}$ (laminar & turbulent flow)		Nu[2]		312.6258					
Nusselt number used		Nu		312.6258		>>>>	Nu no. criteria = 1.00E+09		
Stefan-Boltzmann constant		σ	W/(m^2.K^4)	5.67E-08					
Convective heat transfer coefficient from system		h_c	W/m^2.K	4.20394					
Convective surface resistance of system		R_c	m^2.K/W	0.237872					
Radiant heat transfer coefficient from system		h_r	W/m^2.K	5.92884					
Radiant surface resistance from system		R_r	m^2.K/W	0.1687					
Total surface resistance			m^2.K/W	0.098690			NB: EN ISO 6946 Agrees with these values at surface temp = 25 °C		

Churchill & Chu (1)	Churchill & Chu (2)	Page 431
251.1163581	20.11767	Calculation done in stages
0.81659753	0.816598	to ensure that the
1.81659753	1.193486	equations are calc
1.303845395	312.6258	correctly
193.276729		

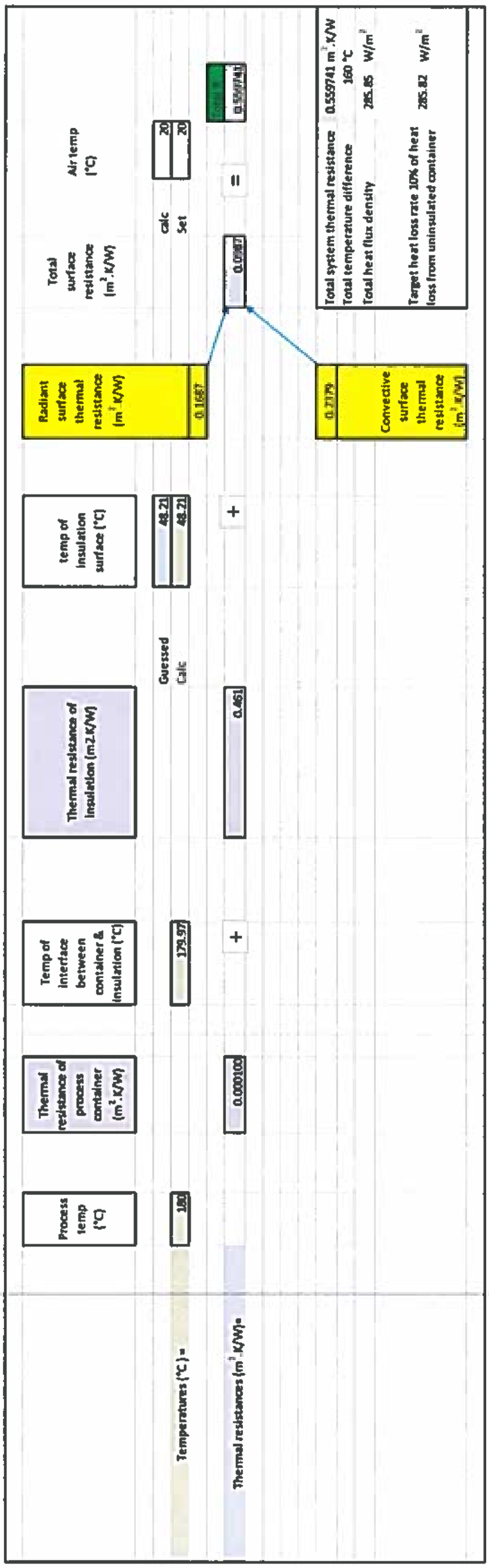
Check of radiant heat transfer coefficient calculation

5.92884 σ .E.$(T1^4 - T2^4)$.F.A (Page 616 Engineering Heat Transfer)

$$h_{rad} = \varepsilon\sigma(T1^2+T2^2)(T1+T2)$$

Checked by: J.W. GTB

Figure 3 The spreadsheet calculation method - Part 2



Process temp (°C)

Thermal resistance of process container (m²·K/W)

Temp of interface between container & insulation (°C)

Thermal resistance of insulation (m2.K/W)

temp of insulation surface (°C)

Radiant surface thermal resistance (m²·K/W)

Total surface resistance (m²·K/W)

Air temp (°C)

Temperatures (°C) = 180 179.97 Guessed 48.21 Calc 48.21 calc 20 Set 20

Thermal resistances (m²·K/W)= 0.000100 + 0.461 + 0.0987 = 0.559741

Radiant surface thermal resistance: 0.1687

Convective surface thermal resistance (m²·K/W): 0.7179

Total system thermal resistance 0.559741 m²·K/W
Total temperature difference 160 °C
Total heat flux density 285.85 W/m²

Target heat loss rate 10% of heat loss from uninsulated container 285.82 W/m²

Checked by: J.W. GTB