SOLAR & THERMAL 1C
SOLAR & THERMAL ENERGY

When considering solar energy, we can look at the transmittance, reflectance and absorptance of glass, across the relevant regions of the electromagnetic spectrum.

Heat transfer can occur through radiation (including solar energy absorptance), convection and conductance. This Technical Document outlines the fundamentals associated with glass and glazing with regards to heat transfer.

THE ELECTROMAGNETIC SPECTRUM

The Sun provides energy across a wavelength region of approximately 150 – 4000 nm, covering the ultraviolet, visible and infrared regions of the electromagnetic spectrum. As a black body, with a temperature of 5778 K, the theoretical spectrum can be determined using Planck's law [1]. ASTM G173-03 [2] provides spectral data for extraterrestrial radiation at the atmosphere and terrestrial solar radiation at the Earth's surface.

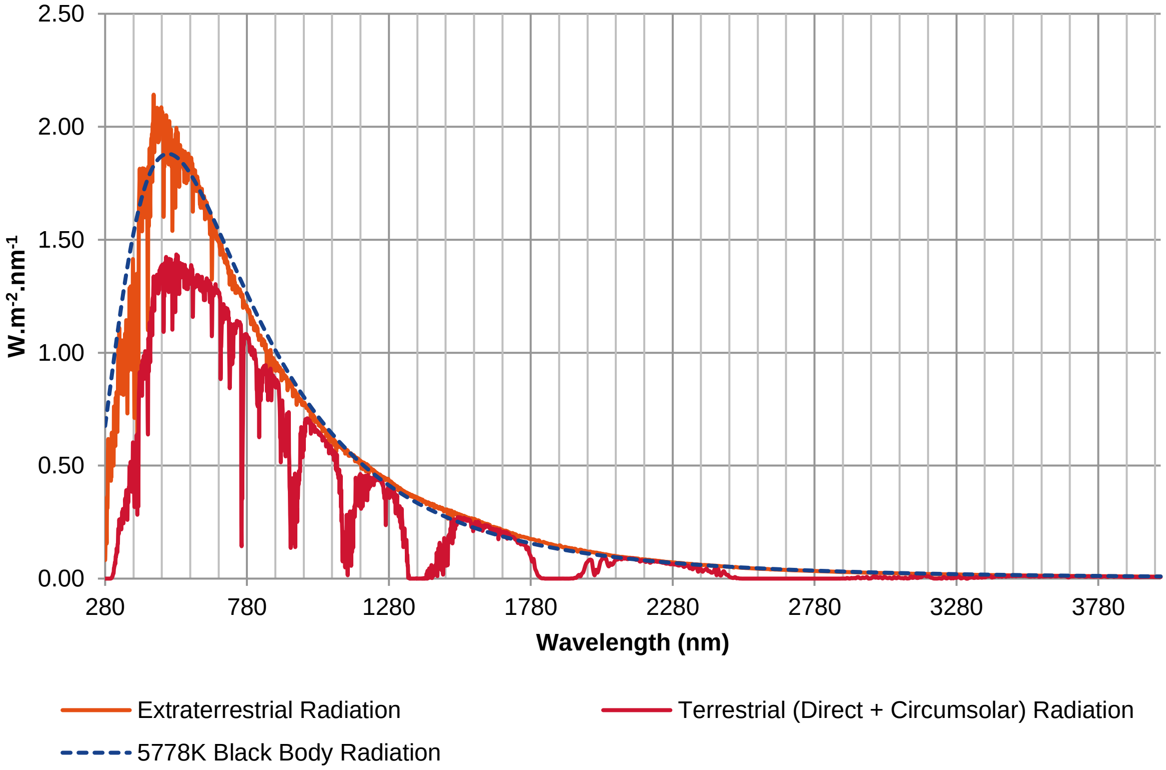

Figure 1 - Electromagnetic spectrum of solar radiation

ENERGY BALANCE

Heat transfer can be considered within a glazing construction in terms of energy balance. With known boundary conditions and energy inputs, the energy into and out of a pane of glass can be considered relative to the surrounding environment. The fundamental of energy balance is for each element transferring and receiving energy to reach a zero sum for absorptance and radiative, conductive and convective heat transfer, effectively a state of equilibrium with regards energy.

Both EN 13363-2 and ISO 15099 [3, 4] provide methods for determining the energy into and out from a system of glazing panes, and this is considered in terms of solar energy absorptance, radiation, conduction and convection. With glazing being a non-IR transmitting material, the relationships can be simplified. In order to reach a steady state, or energy balance conditions, the amount of energy entering the system must equal the amount of energy exiting the system.

The below equation shows the determination of energy balance for a layer within a system;

$$(\alpha_{e,n} \cdot \Phi_s) - h_{r,n-1} \cdot (T_{n-1} - T_n) - h_{r,n+1} \cdot (T_{n+1} - T_n) - h_{c,n-1} \cdot (T_{n-1} - T_n) - h_{c,n+1} \cdot (T_{n+1} - T_n) = 0$$

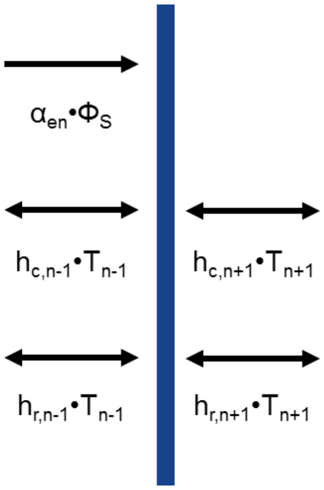

Figure 2 - Energy Balance Schematic

h_r	radiative
h_c	convective/conductive heat transfer coefficient (W/m^2.K)
T	temperature (K)
$\alpha_{e,n}$	solar energy absorptance (Factor, determined from EN 410 [5])
Φ_s	solar flux (W/m^2)

For an external pane, where *n=1*, and so *n-1=0*, the external heat transfer coefficient would be for the external environment, and can be combined for convective, conductive and radiative heat transfer. In this instance, the temperature will typically be considered as the external ambient temperature.

For an internal pane, the internal heat transfer coefficient would be for the internal environment, and can be combined for convective, conductive and radiative heat transfer. In this instance, the temperature will typically be considered as the internal ambient temperature.

SOLAR ENERGY ABSORPTANCE

Solar energy reaches, and influences, the earth, and objects on earth through radiant heat transfer. Fundamental to this, is the solar energy absorptance, which is determined by the spectral properties of a material. Essentially, the solar energy not transmitted through, or reflected by, an object, will be absorbed.

EN 410 [5] uses a relative spectral distribution derived from CIE 85 [6], incorporating wavelength intervals, in order to assess the solar energy transmittance, reflectance and absorptance of glass. The below shows the absorptance profile for 4 mm SGG PARSOL GREY and the relative spectral distribution of solar energy,

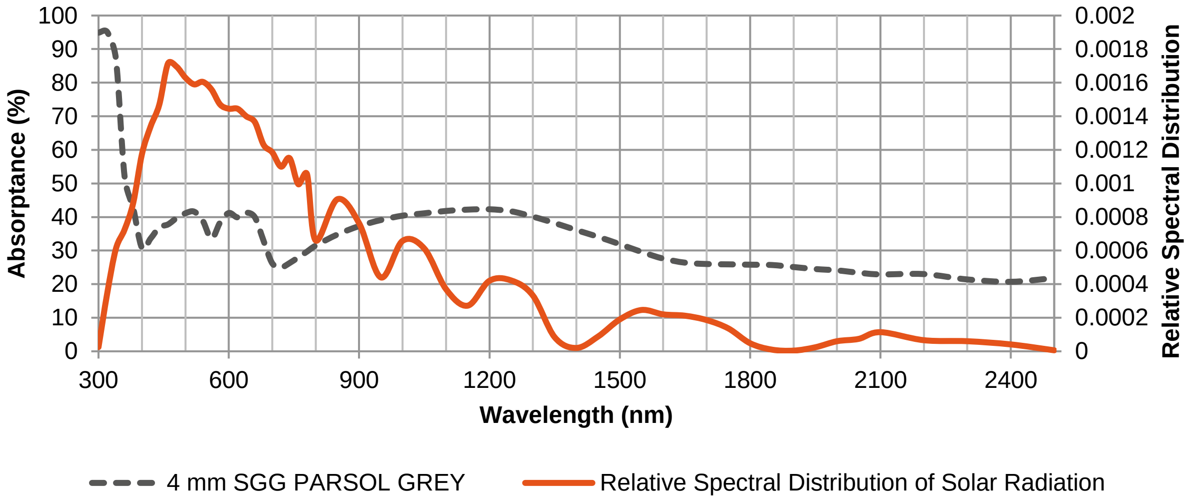

Figure 3 – Solar energy absorption spectra and solar radiation distribution

Multiplying the normalised solar energy distribution by the sample absorptance and the wavelength interval, allows the solar energy absorptance to be determined, which in this instance would be 37.1%. As a percentage, this value would be used in conjunction with the actual levels of solar flux in order to assess the total amount of energy absorbed (W/m^2).

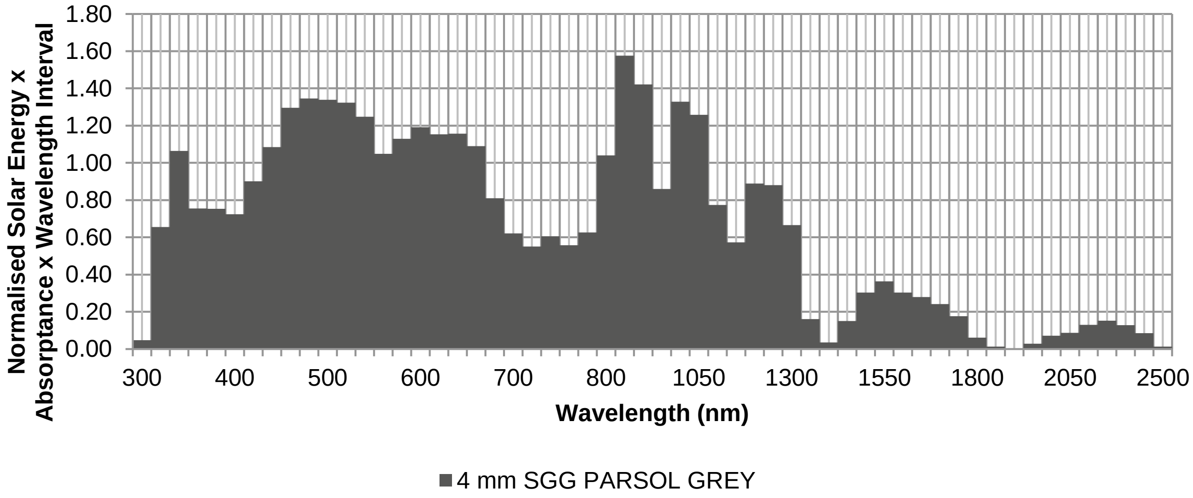

Figure 4 – Absorption profile of 4 mm SGG PARSOL GREY

RADIATIVE HEAT TRANSFER

Radiative heat transfer will occur from an object, as its relative temperature to surrounding objects, and the atmosphere, becomes greater. Radiative heat transfer involves the transfer of energy without physical contact, or transfer through a medium such as a gas or liquid.

Any object above absolute zero will emit thermal radiation, and an object will also receive radiation from other objects. As above, theoretical spectral density of radiation of a black body object emitted can be determined from Planck's law [1], with the below showing the theoretical spectral density of objects at 323 K (50ºC) and 373 K (100ºC).

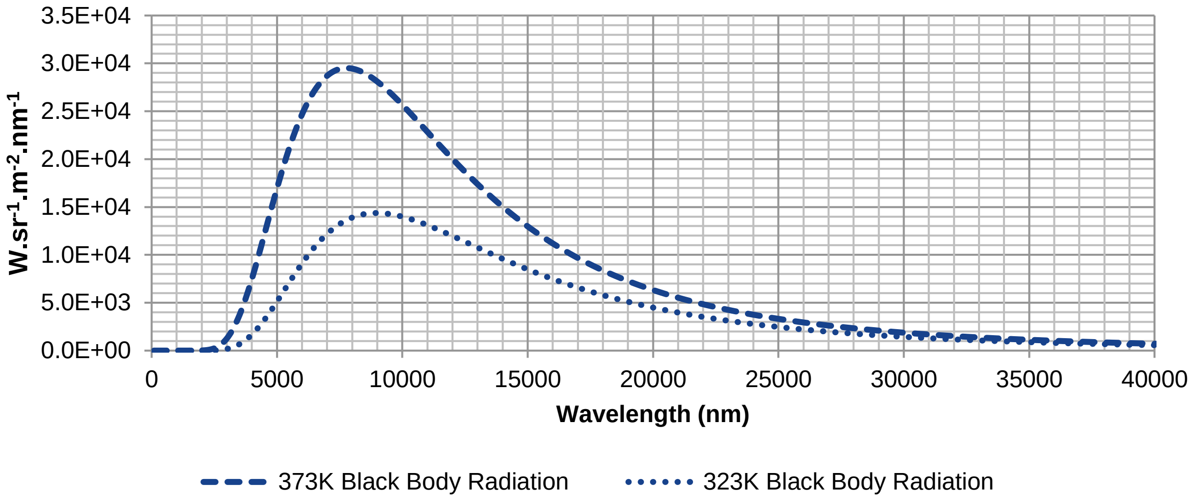

Figure 5 - Electromagnetic spectrum of black body radiation

The rate at which heat is emitted from an object is also dependant on its emissivity. For a perfect emitter, a black body, this is 1.0. Silver is a low emissivity material, and when polished, will have an emissivity in the region of 0.02, and is also used in coated glass types for improved thermal insulation.

Radiative heat transfer is dependent on the emissivities of the bounding surfaces and relative surface temperatures. With consideration to the Stefan-Boltzmann law [7, 8], which states that; "*the total radiant heat energy emitted from a surface is proportional to the fourth power of its absolute temperature*", the emissivity of a grey body, i.e. a surface that doesn't absorb all incoming radiation, can be considered in order to determine radiative power (q, *W/m*^{2}). For glass, emissivity is determined in accordance with EN 12898 [9].

$$q = \varepsilon \cdot \sigma \cdot T^4$$

Where; σ Stefan-Boltzmann Constant, 5.6703 x 10^{-8} W/m^2.K^4

ε Surface Emissivity

T Surface Temperature (K)

RADIATIVE HEAT TRANSFER BETWEEN TWO PARALLEL SURFACES

If two planar surfaces are considered, both grey bodies, as would be the condition within an insulating glazed unit, consideration has to be given to the relative surface temperatures and emissivities. The following relationship applies;

$$q_{1\to 2} = \frac{\sigma \cdot (T_1^4 - T_2^4)}{\left(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1\right)}$$

The derivation of this relationship is available in Document **ST-5A UNDERSTANDING EMISSIVITY**.

As thermal energy will radiate from a warmer surface towards a cooler one, the heat transfer will be positive or negative depending on the relative surface temperatures. From the above, the radiate heat transfer coefficient, h_r (W/m^2.K), can also be determined, as follows;

$$h_r = \frac{q}{\Delta T}$$

Thus, yielding;

$$h_r = \frac{\sigma \cdot (T_1^4 - T_2^4)}{\left(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1\right) \cdot (T_1 - T_2)}$$

With regards glass, and the application of low emissivity coatings, the reduction in the radiative heat transfer can be significantly reduced, as illustrated below;

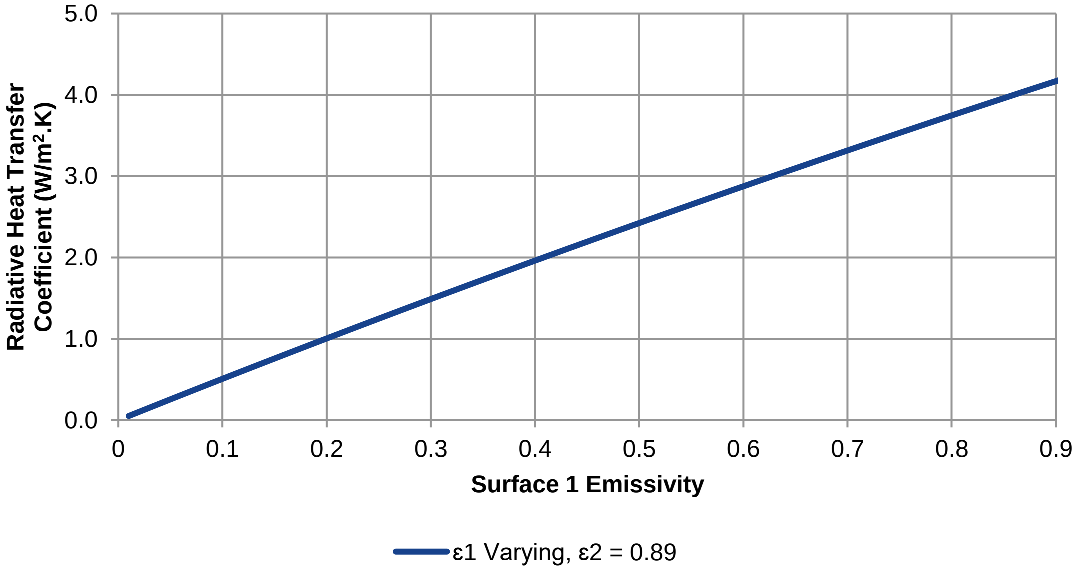

Figure 6 - Radiative Heat Transfer as a Function of the Emissivity

The absolute and relative temperature differences will also influence the radiative heat transfer. The below is based on linearly diverging surface temperatures, averaging 283 K, and as such commencing at conditions $T_1 = T_2 = 283$ K.

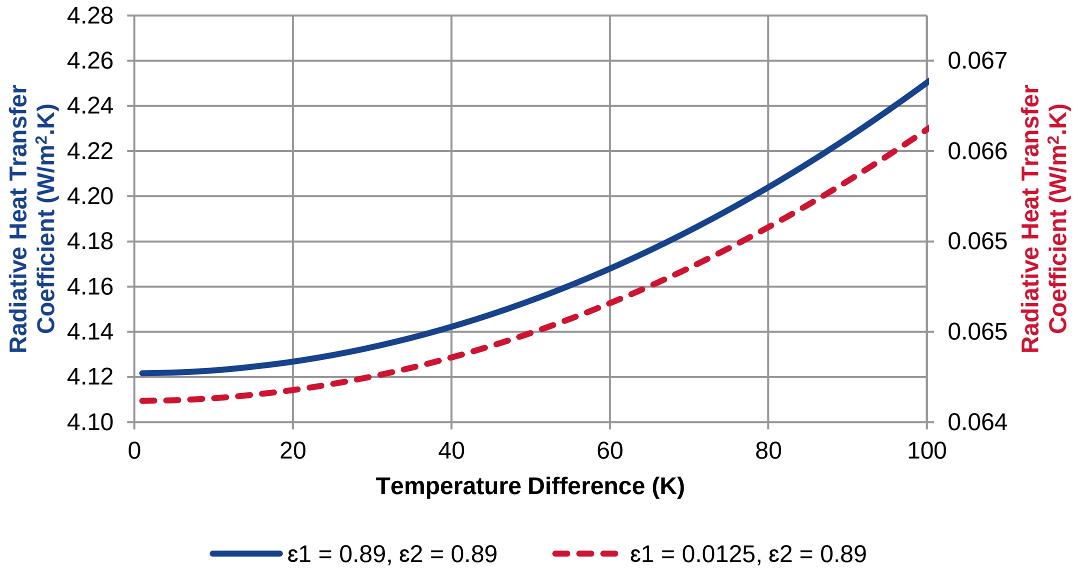

Figure 7 - Radiative Heat Transfer as a Function of the Temperature Differential

SIMPLIFIED RADIATIVE HEAT TRANSFER

Where pane temperatures may not be known, or set boundary conditions are being worked to, such as with EN 673 [10], the following relationship can be applied;

$$h_r = \frac{4 \cdot \sigma \cdot (T_m^3)}{\left(\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1\right)}$$

Where; T_m Mean Temperature between the 2 Surfaces (K)

This relationship provides a reasonable level of accuracy with both average surface temperature changes alongside one of the surface temperature, i.e. the pane temperatures are not divergent (top chart), and where surface temperatures diverge (bottom chart). The radiant heat transfers by each method would typically differ by up to 2% for realistic temperature ranges, as illustrated below;

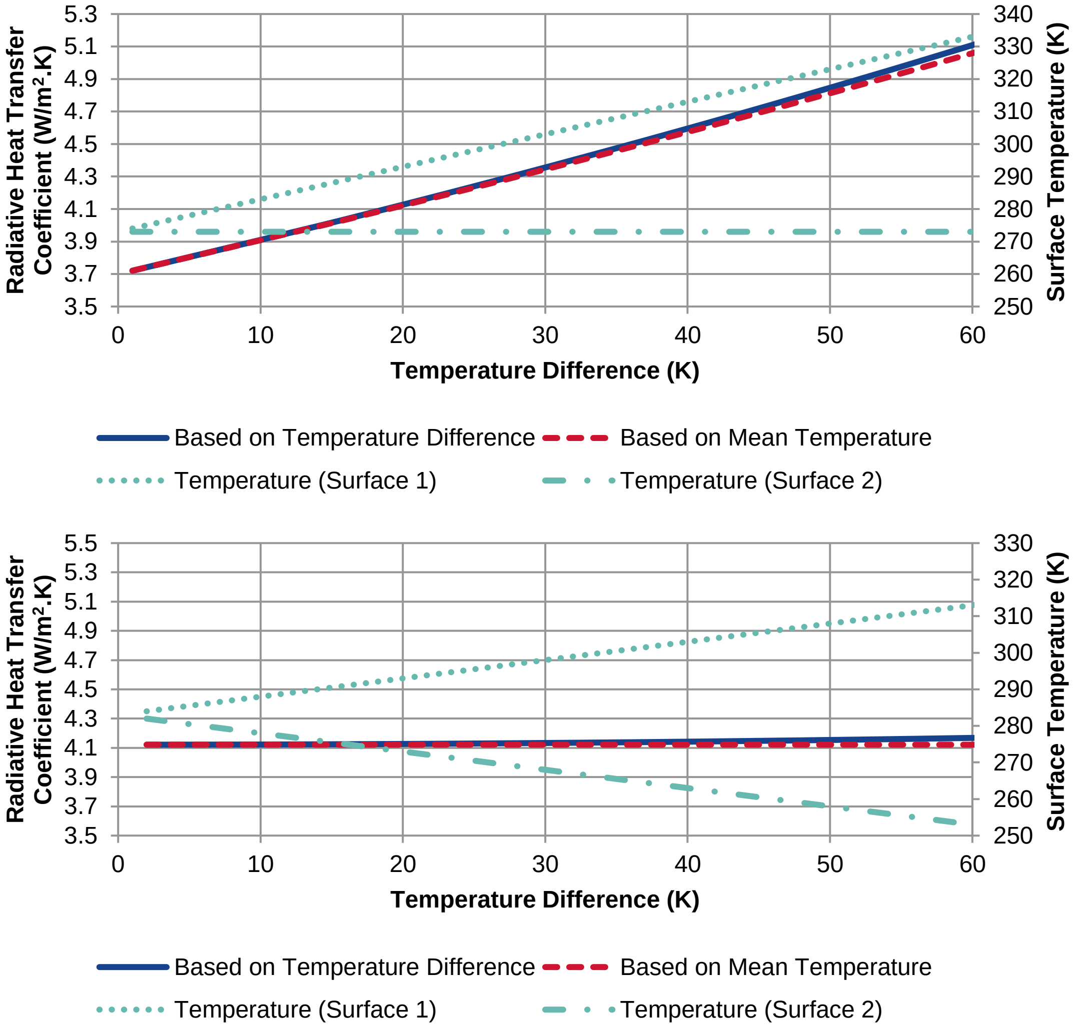

Figure 8 - Radiative Heat Transfer as a Function of Temperature Differentials and Mean Temperatures

CONDUCTIVE & CONVECTIVE HEAT TRANSFER

When considering insulating glass units and energy transfer, both conduction and convection will need to be considered.

CONDUCTIVE HEAT TRANSFER

Conduction takes place when objects are physically touching, whether they are solid, liquid or gas, with the molecules in a warmer object increasing the energy of materials in a cooler object.

For example, if a heated metal bar is placed against one end of a cold metal bar, then the cooler bar will begin to heat up, initially in the region of contact with the warmer bar. Over time, the two bars will begin to approach the same temperature as the molecules in the warmer regions of the second bar transmit energy sequentially into the colder areas. This is illustrated in Figure 9

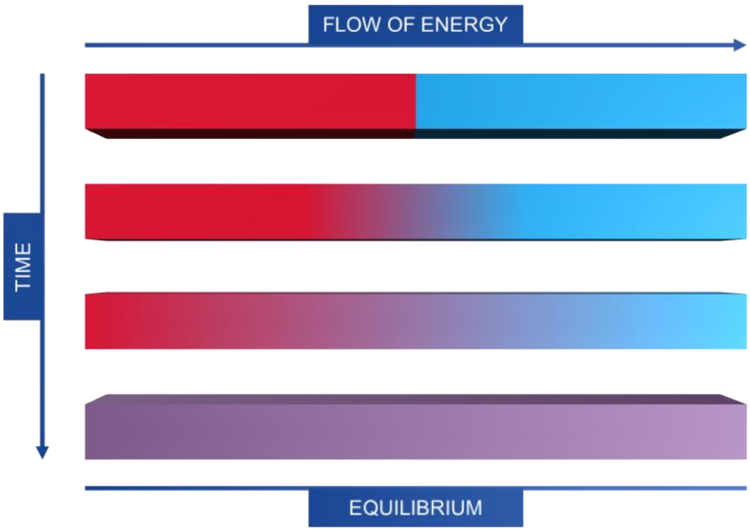

Figure 9 - Heat Transfer through Conduction

Different materials conduct heat at different rates, depending upon their molecular structure. Metals for example, conduct heat far more effectively than glasses, plastics or gases. For glazing, of particular interest is gas conductance, as double glazing will rely on conductance across a cavity to improve thermal insulation.

CONVECTIVE HEAT TRANSFER

Convection happens in liquids and gases, and unlike solids where molecules can only vibrate, the process involves heat energy moving through a material as the molecules themselves move through the material. As a liquid or gas gains more energy, the molecules move further apart and so the liquid or gas becomes less dense.

Convection currents occur as the less dense portions of the liquid or gas move rise above the colder regions. For example, when a radiator heats air in a room, that air, being less dense, will rise. As it does so, it will transfer energy to the cooler regions of air, become denser, and then fall below the more recently heated regions of air. If we consider the flow in discrete regions, it can be illustrated as below:

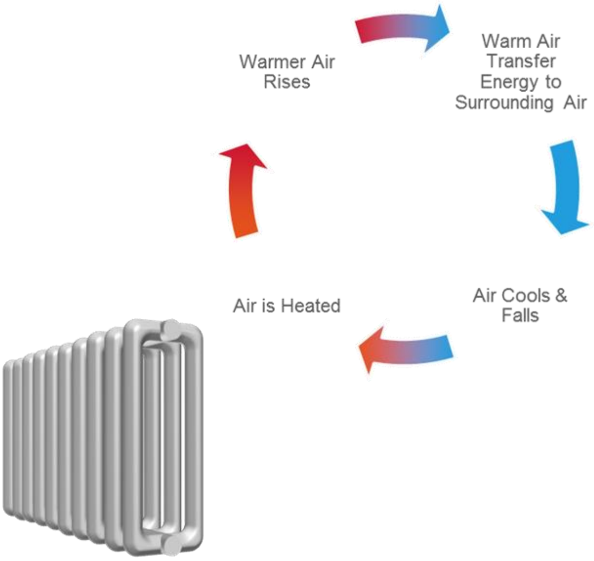

Figure 10 - Convective Heat Transfer

INSULATING GLASS UNIT CAVITY CONVECTIVE & CONDUCTIVE HEAT TRANSFER

Combined convective and conductive heat transfer (h_c) can be considered by the conductivity of the gas (λ), the width of the gas space (t), and the Nusselt number (Nu), which defines the relationship between convective and conductive heat at a boundary.

$$h_c = Nu \cdot \frac{\lambda}{t}$$

The Nusselt number can be related to the Rayleigh (Ra) number, which in turn is related to the Grashof (Gr) and Prandtl (Pr) numbers, all dimensionless values, as below;

$$Ra = Gr \cdot Pr$$

Where;

$$Gr = \frac{g \cdot t^3 \cdot (T_n - T_{n+1}) \cdot \rho^2}{\left(\frac{T_n + T_{n+1}}{2}\right) \cdot \mu^2}$$

And;

$$Pr = \frac{\mu \cdot c}{\lambda}$$

Where;	g	Acceleration due to Gravity, 9.81 m/s^2
	ρ	Density of Gas (kg/m^3)
	T	Surface Temperature (K)
	μ	Dynamic Viscosity (kg/m.s)
	c	Specific Heat Capacity (J/kg.K)
	λ	Conductivity (W/m.K)

The relationship between the Rayleigh and Nusselt numbers is defined with EN 673 as a constant, A, and an exponent, n, as follows;

$$Nu = A \cdot (Gr.Pr)^n$$

Where A and n are dependent on the angle from horizontal, as follows;

0º from Horizontal	A = 0.160, n = 0.28
45º from Horizontal	A = 0.100, n = 0.31
90º from Horizontal (Vertical)	A = 0.035, n = 0.38

An alternative relationship is defined within ISO 15099, which considers different fits for the Nusselt/Rayleigh relationship based on the glazing angle. For vertical glazing, ISO 15099 considers two fits, one based on boundary conditions for the Rayleigh number, and another based on a coefficient and exponent, with a factor the ratio of cavity height to thickness. The maximum of the two is used for the purposes of further calculations.

For high ratios of cavity height to thickness, both EN 673 and ISO 15099 give comparative results, as shown below for an aspect ratio of greater than 25.

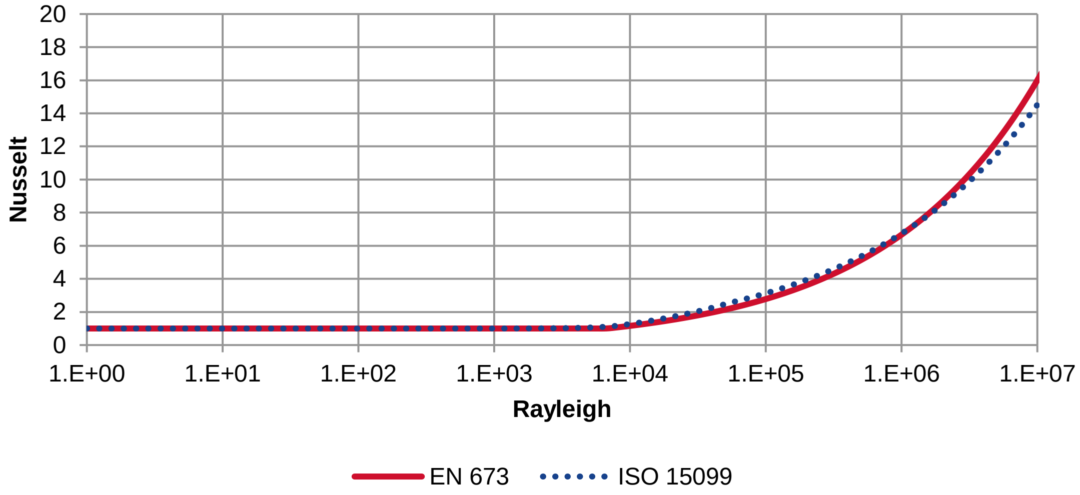

Figure 11 - Nusselt, Rayleigh Relationship as defined by EN 673 & ISO 15099

However, for lower aspect ratios, as may be found in low height units, with wider cavities, for example, there is some deviation, as shown in Figure 12, for an aspect ratio of 5.

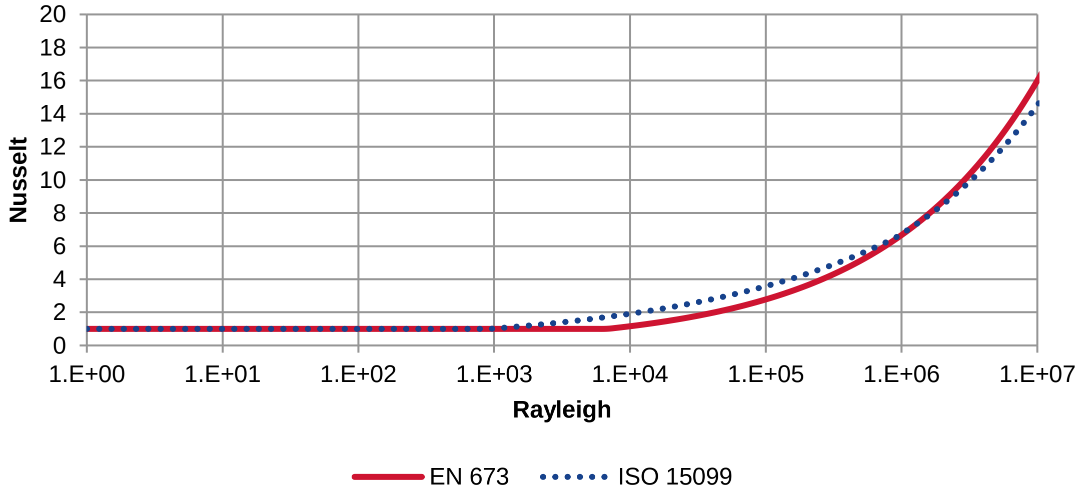

Figure 12 - Nusselt, Rayleigh Relationship as defined by EN 673 & ISO 15099 (Aspect Ratio = 5)

THERMAL INSULATION

One of the key parameters for glazing is the U value, and for the purposes of CE marking, and values used with reference to Building Regulation requirements, this can be determined for pre-defined boundary conditions in accordance with EN 673. This is detailed within document **ST-1E THERMAL INSULATION**.

REFERENCES

[1] M. Planck, Vorlesungen über die Theorie der Wärmestrahlung, Leipzig: Verlag Von Johann Ambrosius-Barth, 1906.

[2] ASTM, *ASTM G173-03,* ASTM International, 2012.

[3] European Committee for Standardization, EN 13363-2:2005 - Solar protection devices combined with glazing. Calculation of total solar energy transmittance and light transmittance. Detailed calculation method, CEN, 2005.

[4] International Organization for Standardization, ISO 15099:2003 - Thermal performance of windows, doors and shading devices. Detailed calculations, ISO, 2003.

[5] European Committee for Standardization, EN 410:2011 - Glass in building. Determination of luminous and solar characteristics of glazing, CEN, 2011.

[6] Commission Internationale de l'Eclairage, *Solar spectral irradiance, technical report,* CIE, 1989.

[7] J. Stefan, “Über die Beziehung zwischen der Wärmestrahlung und der Temperatur,” *Sitzungsberichte der Kaiserlichen Akademie der Wissenschaften in Wienn,* vol. 79, pp. 391-428, 1879.

[8] L. Boltzmann, “Ableitung des Stefan'schen Gesetzes, betreffend die Abhängigkeit der Wärmestrahlung von der Temperatur aus der electromagnetischen Lichttheorie,” *Annalen der Physik,* vol. 258, no. 6, pp. 291-294, 1884.

[9] European Committee for Standardization, EN 12898:2001 - Glass in building. Determination of the emissivity, CEN, 2001.

[10] European Committee for Standardization, EN 673:2011 - Glass in building. Determination of thermal transmittance (U value). Calculation method, CEN, 2011.