RADIATION HEAT TRANSFER EXPERIMENT

1. Object

The purpose of this experiment is to study details of radiation heat transfer mechanism and test parameters of radiation heat transfer experiment.

2. Introduction

There are three modes of heat transfer. These are conduction, convection and radiation. Conduction is the transfer of heat from an atom (molecule) to an atom (molecule) within a substance. Convection is a heat transfer mode that occurs between a surface and a moving fluid when they have different temperatures.

Radiation is energy transfer across a system boundary due to a temperature difference ΔT. The energy of radiation is transported by electromagnetic waves or photons. Thermal radiation can occur in solids, liquids, and gases. Also, it occurs at the speed of the light so it is the fastest heat transfer mode.

While the transfer of energy by conduction or convection requires the presence of a material medium, radiation does not. The significance of this is that radiation is the only mechanism for heat transfer that can occur in the vacuum.

Likewise, as shown in the Figure 1, heat energy can reach to the Earth from the Sun although there are no particles between the Sun and the Earth.

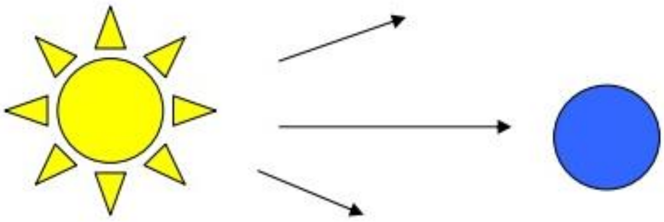


Figure 1. Radiation heat transfer between the Sun and the Earth.

All bodies with a temperature above absolute zero (0 K) radiate energy in the form of photons moving in a random direction, with random phase and frequency. When radiated photons reach another surface, they may be absorbed, reflected or transmitted. The behavior of a surface with radiation incident upon it can be described by the following quantities:

α : Absorptance - fraction of the incident radiation absorbed
ρ : Reflectance - fraction of the incident radiation reflected
τ : Transmittance - fraction of the incident radiation transmitted

The Figure 2 shows these processes graphically.

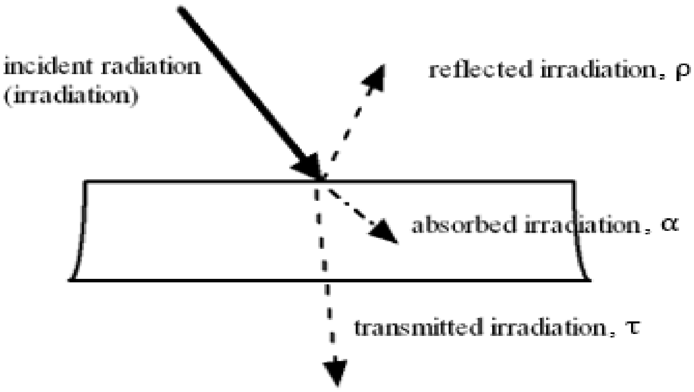


Figure 2. Radiation at a surface.

From energy considerations, these three coefficients must sum to unity as shown in the Equation 1.

$$\propto + \rho + \tau = 1 \tag{1}$$

Reflective energy may be either diffuse or specular (mirror-like). Diffuse reflections are independent of the incident radiation angle. For specular reflections, the reflection angle equals the angle of incidence.

3. Theory

3.1 The Stefan-Boltzmann law

The Stefan-Boltzmann law that is defined by equation 2 states that for a black body

$$q_b" = \sigma(T_s^4 - T_{sur.}^4) \tag{2}$$

Where

$q_b"$: Energy radiated by a black body per unit area, (W/m^2)
σ : The Stefan-Boltzmann constant, $\sigma = 5.67 \cdot 10^{-8}$ W/($m^2 \cdot$ K^4)
T_s : Surface temperature of the heated plate, (K)
$T_{sur.}$: Surrounding temperature including the radiometer, (K)

The reading on the radiometer will be related to the radiation emitted by the plate through a constant factor *F* as shown in the Equation 3.

$$F = \frac{q_r"}{q_b"} \tag{3}$$

$q_r"$: Radiation received by the radiometer, (W/m^2)
F : View factor (-)

3.2 Radiation intensity

The radiation received by the radiometer is connected to the radiation emitted by the source through the view factor *F* defined as fraction of energy emitted in unit time by a surface intercepted by the other surface. In this case, we have equation 4 which is

$$q_b" = F\sigma(T_s^4 - T_{sur.}^4) \tag{4}$$

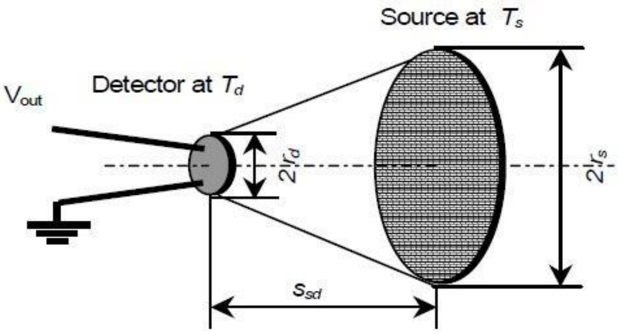
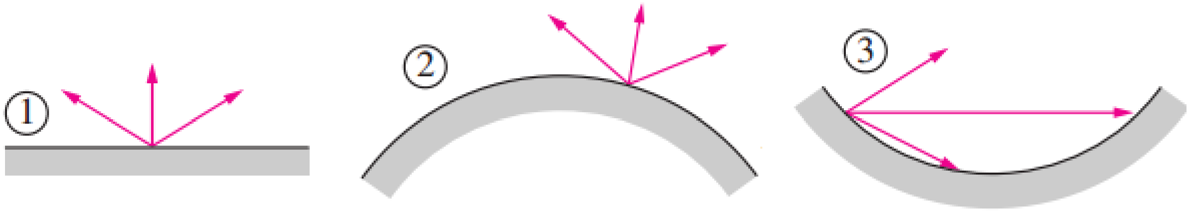


Figure 3. View factor between a circular detector and a circular source.

$$F_{sd} = \frac{2\pi r_d^2}{r_s^2 + r_d^2 + s_{sd}^2 + \sqrt{(r_s^2 + r_d^2 + s_{sd}^2)^2 - 4r_s^2 r_d^2}} \quad (5)$$

The view factor F only depends on geometrical parameters. The view factor from surface i to surface j is denoted by F_{ij}. F_{ij} is the fraction of the radiation leaving surface i that strikes surface j directly. F_{ii} is the fraction of radiation leaving surface i that strikes itself directly. For plane or convex surfaces $F_{ii} = 0$ for concave surfaces $F_{ii} \neq 0$ (figure 4).



(a) (b) (c)

Figure 4. View factor for (a) plane surface (b) convex surface (c) concave surface.

3.3 View factor relations

Radiation analysis on an enclosure (circle, triangle etc.) consisting of N surfaces requires the evaluation of N^2 view factors. There are four fundamental relations to be able to evaluate view factors.

3.3.1 The Reciprocity Rule

That the pair of view factors F_{ij} and F_{ji} are related to each other is given by equation 6

$$A_i F_{ij} = A_j F_{ji} \quad (6)$$

This relation is referred to as the reciprocity relation or the reciprocity rule.

Note that $F_{ij} = F_{ji}$ when $A_i = A_j$, $F_{ij} \neq F_{ji}$ when $A_i \neq A_j$.

3.3.2 The summation rule

The sum of the view factors from surface *i* of an enclosure to all surfaces of the enclosure as shown in the figure 5, including to itself, must equal unity as stated in the equation 7.

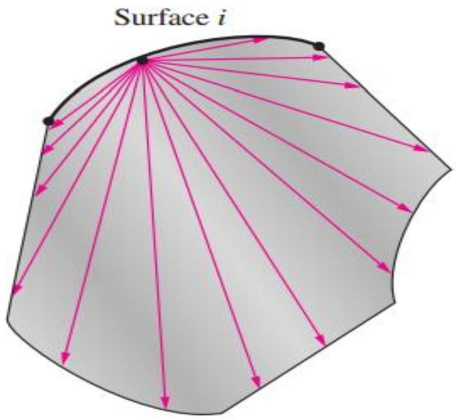


Figure 5. Radiation leaving surface *i*.

$$\sum_{j=1}^{N} F_{ij} = F_{i1} + F_{i2} + \cdots + F_{iN} = 1 \qquad (7)$$

3.3.3 The superposition rule

Superposition rule states that the view factor from a surface *i* to a surface *j* is equal to the sum of the view factors from surface *i* to the parts of surface *j*. Consider the geometry shown in the figure 6 below. The view factor from surface 1 to the combined surface of 2 and 3 is calculated from equation 8.

$$F_{1\rightarrow(2,3)} = F_{12} + F_{13} \qquad (8)$$

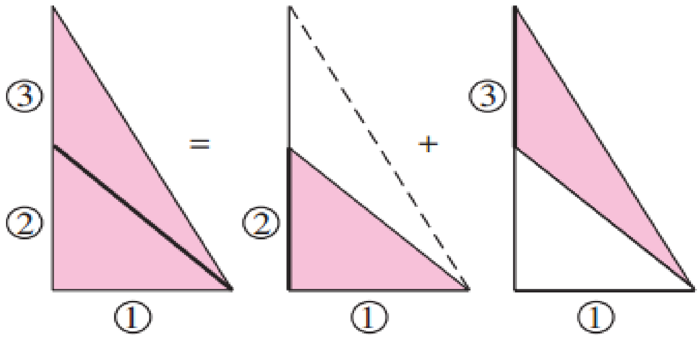


Figure 6. Radiation leaving surface 1.

3.3.4 The symmetry rule

As shown in the figure 7 two (or more) surfaces that possess symmetry about a third surface will have identical view factors from that surface.

$$F_{12} = F_{13} \qquad (9)$$

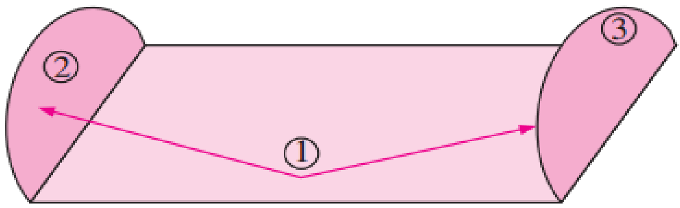


Figure 7. Symmetry between the surface 1 and the surfaces 2, 3.

3.4 Emissivity of radiating surfaces

The Stefan-Boltzmann law states that

$$q_b = \varepsilon F \sigma (T_s^4 - T_a^4) \tag{10}$$

Where ε is the emissivity of the radiating surface and $\varepsilon = 1$ for a black body. If a black plate is set on a proper support between the radiating surface and the radiometer and considering that the plate is not circular but square, the view factor will change. In this case, the emissivity of the plate set between the heat source and the radiometer is equal to

$$\varepsilon = \frac{R}{\sigma F (T_s^4 - T_a^4)} \tag{11}$$

3.5 Radiating energy

Considering the simple case in which a small hot surface at temperature T_a and with an area of A_a is surrounded by a quite wide cold surface at temperature T_b and with an area of A_b, the radiating energy exchange, q_{ab} between two black surfaces is given by equation 12.

$$q_{ab} = \sigma A_a F_{ab} (T_a^4 - T_b^4) \tag{12}$$

This simple equation can be applied to the radiation from the heated plate to the surrounding environment at surrounding temperature, $T_{sur.}$. Actually, the radiometer is a small area of the surrounding at temperature, $T_{sur.}$.

3.6 Lambert's cosine law for light

The Lambert's law for diffused radiation states that the radiant intensity along a beam is directly proportional to the cosine of the angle between the beam and a line perpendicular to the radiating surface.

$$l_\phi = l_0 cos\phi \tag{13}$$

Where

l_0 **:** Radiant intensity in perpendicular direction to the surface i.e. for $\phi = 0°$, (lux)

l_ϕ **:** Radiant intensity at angle ϕ in respect to normal direction, (lux)

3.7 Lambert's law of absorption

The Lambert's law of absorption states that the luminous intensity of light (l_f) decreases exponentially with the distance t that it enters an absorbing medium with a linear absorption coefficient, α. The light intensity (l_f) of the beam striking the absorbing filter is given by equation 14.

$$l_f = l_0 e^{-\alpha t} \tag{14}$$

Where
l_0 **:** Light intensity of the incident beam, (lux)
l_f **:** Light intensity after crossing the filter, (lux)
t **:** Filter thickness, (m)
α **:** Absorbing capacity of the filter material.

The light intensity is reduced due to the light absorption by the material. The absorbed quantity depends on the filter thickness and the absorbing capacity of the filter material.
In practice, part of the light is reflected on the front surface of the filter and does not cross the same filter. Therefore, it is necessary to detect this value of reflected light when the absorption inside the filter is considered. The equation written above must be corrected to include this reflected loss (l_r) as follows:

$$l_f = (l_0 - l_r)e^{-\alpha t} \tag{15}$$

4. Experiments to be Performed
The experimental setup will be introduced in the laboratory before the experiment by the relevant researching assistant.

4.1 Experimental setup
The experimental setup includes a horizontal support and a heat radiation source as shown in the figure 8. Radiometer and other devices related to the experiment can be placed to this support. Radiometer and each device must be placed to relevant holder. These holders can be moved through a rail system.

Heat radiation source gain energy through measurement and control panel. Temperature of metal plates with thermocouples can be read on digital thermometer. The signals from radiometer are received by socket *D*.

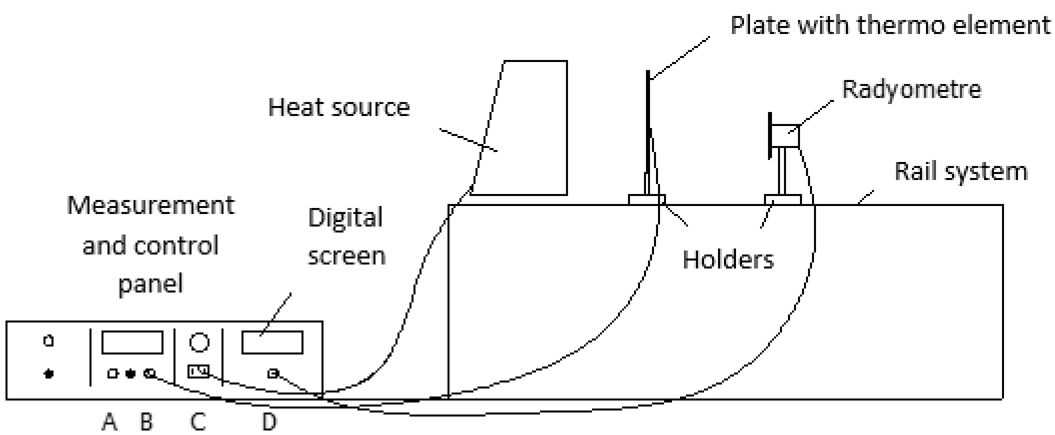


Figure 8. The experimental setup

4.2 Experiments

4.2.1 The Stefan – Boltzmann law

$$q_s'' = \sigma(T_s^4 - T_{sur.}^4) \tag{16}$$

Where

q_b" : Energy radiated by a black body per unit area, (W/m^2)
σ : The Stefan-Boltzmann constant, $\sigma = 5.67 \cdot 10^{-8}\ \mathrm{W}/(m^2 \cdot \mathrm{K}^4)$
T_s : Surface temperature of the heated plate, (K)
$T_{sur.}$: Surrounding temperature including the radiometer, (K)

The positions of radiometer and the plate are shown in the figure 9.

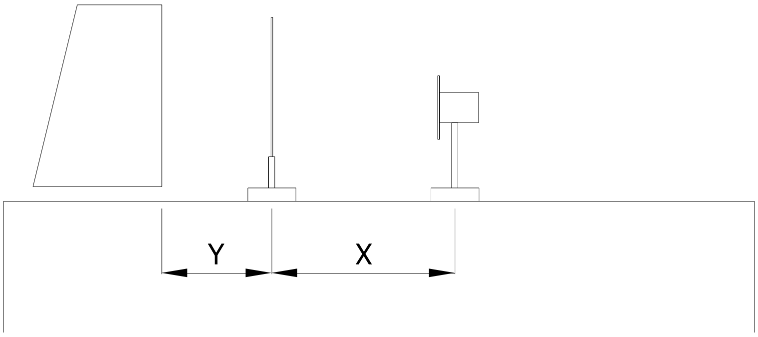


Figure 9. The positions of the radiometer and the plate.

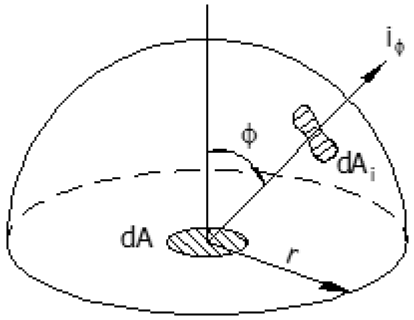
The distance between radiometer and the plate is $x = 60$ mm
The distance between the plate and the heat source is $y = 50$ mm

Plate temperature	Radiometer	Heat flux ( )		Emissivity
		Calculated	Measured	
T_s (K)	R (W/m^2)	$q_s" = \sigma(T_s^4 - T_{sur.}^4)$	$q_b" = 4.9R$	$\varepsilon = \frac{q_b}{q_s}$
303.15				
313.15				
323				
333				
343				
353				
363				
373				

Measurements
The value of the temperature and radiometer should be read at different surrounding temperatures.

Requested
Compare and make a comment about two heat radiation values for black body and explain the differences between these two values.

4.2.2 Inverse square law
The intensity of radiation inversely proportional to square of the distance from the source.



Total radiation emitted from dA element that is in the center of a sphere with radius r is dQ. Solid angle for dA_1 surface element is $d\omega_\phi = \frac{dA_1}{r^2}$. If i_ϕ is the radiation intensity in the direction of ϕ, radiation energy passing from dA_1 element is

$dQ = i_\phi d\omega_\phi dA$

x: The distance between radiometer and the black body.

Distance, x (mm)	100	200	300	400	500	600	700
Radiometer, R ()							
$\text{Log}_{10}x$							
$\text{Log}_{10}R$							

Measurements

Read heat radiation values from radiometer starting from X = 100 mm.

Requested

Draw a graph of change between $\log_{10}$X - $\log_{10}$R. (Place $\log_{10}$X to the horizontal axis and $\log_{10}$R to the vertical axis). Find the equation and correlation coefficient of this graph. Make a comment about radiation intensity and distance change using the slope of the graph.

4.2.3 Emissivity

Emissivity is the ratio of radiation emitted by a surface and radiation emitted by a black body at the same temperature. Emissivity depends on wavelength of radiation, surface temperature and surface roughness. However, in the most of the engineering applications, emissivity is assumed as constant.

The distance between radiometer and the plate is x = 60 mm
The distance between the plate and the heat source is y = 50 mm

Plate Temperature	**Radiometer**	**Heat Flux**		**Emissivity**
		Calculated	**Measured**	
T_s (K)	R	$q_s" = \sigma(T_s^4 - T_{sur.}^4)$	$q_b = 4.9R$	$\varepsilon = q_b/q_s$
303.15				
313				
323				
333				
343				
353				
363				
373				

Measurements
In this experiment, emissivities of two different plates will be calculated. For these calculations, we need radiosity values for different temperatures.

Requested
Calculate an average emissivity for both plates. Compare these values with emissivity of a black body.

4.2.4 View factor
View factor can be calculated using analysis, numerical methods and analogy. View factors for common geometries are determined and can be found from related textbooks.
For view factor experiment, the positions of the plates are shown in the figure 10.

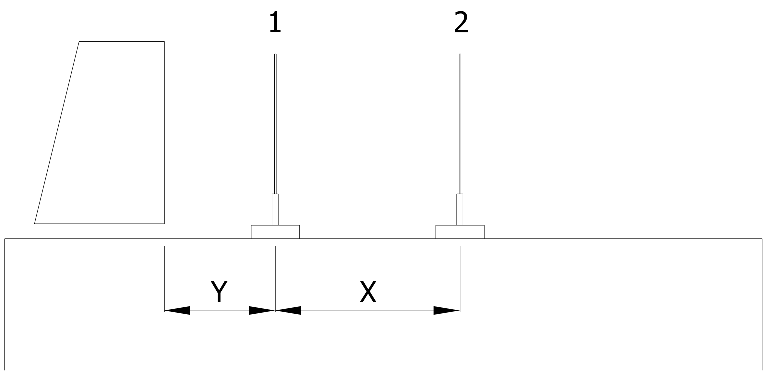
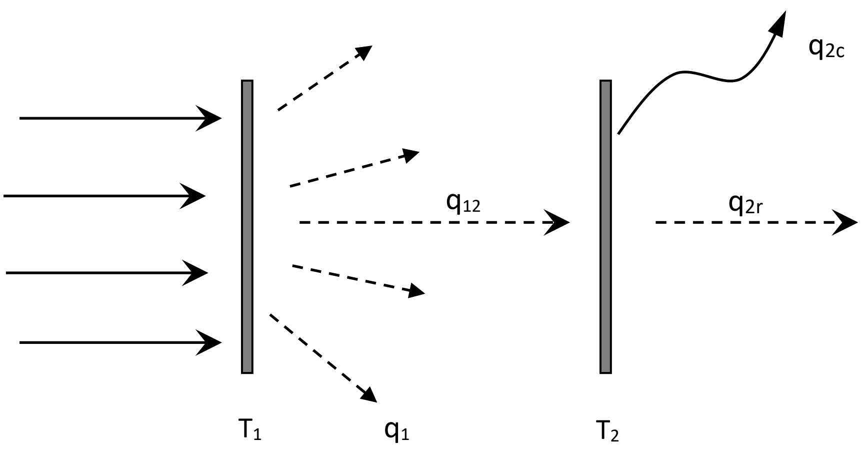


Figure 10. The positions of the plates for view factor experiment

The distance between two plates x = 100 mm
The distance between first plate and heat source y = 50 mm

Measurements
The temperatures of two black plates will be measured.



Calculations
Total heat transfer from plate 1 $q_1 = \varepsilon_1 \sigma {T_1}^4 A$
Radiation heat transfer from plate 2 to the surrounding $q_{2r} = \varepsilon_2 \sigma ({T_2}^4 - {T_{sur.}}^4) A$
Heat transfer by convection from plate 2 to the environment $q_{2c} = h(T_2 - T_{sur.}) 2A$

When the system reach the balance thermodynamically, $q_{12} = q_{2r} + q_{2c}$ and view factor can be calculated from $F_{12} = q_{12}/q_1$.

To be able to calculate heat transfer by natural convection from plate 2 to the environment, we should determine the convection heat transfer coefficient (W/m^2). For this calculation, we will evaluate Rayleigh Number and Nusselt Number respectively. We can calculate Rayleigh Number by equation 17.

$$Ra = GrPr = \frac{g\beta\Delta T L^3}{\nu\alpha} \tag{17}$$

In this equation;
g : Gravitational acceleration, (m/s^2)
β : Thermal expansion coefficient, (K^{-1})
ΔT : Temperature difference between surface and the environment
L : Characteristic length, (m)
ν : Kinematic viscosity, (m^2/s)
α : Thermal diffusivity, (m^2/s)

For ideal gases, thermal expansion coefficient can be calculated from $\frac{1}{\beta} = T_f = \frac{T_2 + T_{sur.}}{2}$
All thermophysical properties must be calculated at film temperature, T_f. For natural convection heat transfer from horizontal plate, characteristic length must be taken as height of the plate. The height of the plates is 160 mm and the width of the plates is 100 mm. Nusselt Number can be calculated from equation 18 using "C" and "n" values for related Rayleigh Number given below.

Ra<10^9 ⟹ $C = 0.59, \quad n = 1/4$ (Laminar)
Ra≥10^9 ⟹ $C = 0.15, \quad n = 1/3$ (Turbulent)

$$Nu = CRa^n = \frac{hL}{k} \tag{18}$$

Thermal conductivity, k W/(m·K) must be calculated at film temperature.

Requested
Calculate the view factor using emissivities you obtained from the previous experiment. Also, compare the view factor you obtained from the experiment with the view factor you calculated using the equation 19 or you can calculate the view factor from the graph shown in figure 11.

$\bar{a} = \frac{a}{c}$ ve $\bar{b} = \frac{b}{c}$ olmak üzere;

$$F_{12} = \frac{2}{\pi \bar{a}\bar{b}} \left\{ \ln\left[\frac{\left(1+\bar{a}^2\right)\left(1+\bar{b}^2\right)}{1+\bar{a}^2+\bar{b}^2} \right]^{1/2} + \bar{a}\left(1+\bar{b}^2\right)^{1/2} \tan^{-1}\frac{\bar{a}}{\left(1+\bar{b}^2\right)^{1/2}} \right. \quad (19)$$

$$\left. + \bar{b}\left(1+\bar{a}^2\right)^{1/2} \tan^{-1}\frac{\bar{b}}{\left(1+\bar{a}^2\right)^{1/2}} - \bar{a}\tan^{-1}\bar{a} - \bar{b}\tan^{-1}\bar{b} \right\}$$

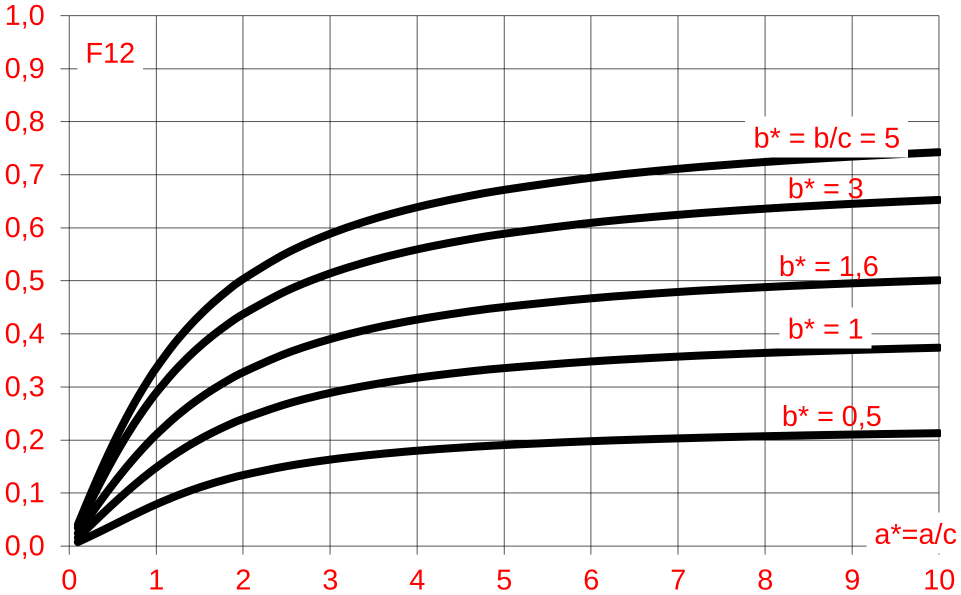


Figure 11. View factor for plates parallel to each other.