Journal of Hazardous Materials, 20 (1988) 137–146
Elsevier Science Publishers B.V., Amsterdam – Printed in The Netherlands

Radiative Interchange Factors Between Flames and Tank Car Surfaces

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Summary

The radiative interchange factors between a flame and tank car surfaces within and outside the flame have been calculated for several commonly occurring geometries. These include the case of the interaction between a pool fire and a turbulent diffusion flame.

Data are presented on the heat flux from a pool fire to a cylindrical surface within the fire with and without the presence of a turbulent diffusion flame jet.

INTRODUCTION

One event which often occurs in a rail accident involving tank cars containing liquefied gaseous fuel under pressure is an unruptured tank car surrounded by burning fuel which has been released from a nearby ruptured tank car. As the undamaged tank car is heated by the fire the pressure within the unruptured tank increases until the pressure relief valve opens releasing a jet of fuel at a high velocity which ignites forming a turbulent diffusion flame.

This paper presents the radiative interchange factor between the flame of a pool fire and a horizontal surface within the flame and the radiative interchange factor between a turbulent flame jet within a pool fire and a horizontal surface within the pool fire flame.

Experimental measurements are presented for the heat flux to sections of a horizontal cylinder surrounded by a propanol pool fire with and without a turbulent propane jet present and with the turbulent propane jet directly impinging on the cylinder.

Radiative Interchange Factors

A compilation of radiative interchange factors associated with naturally occurring fires was presented a number of years ago by Steward (1). Some more recent studies have been made for determining the radiative interchange factors between a pool fire and a tank car surface (2-6). Three studies have been performed on determining the radiative transfer from a turbulent diffusion flame and a tank car surface (2, 7, 8).

The radiative interchange factor between a pool fire and a surface within the fire can be determined from the triple integral

$$\frac{d^2 gs}{dA} = \int_h^Z \int_0^{R(z)} \int_0^{\pi} \frac{2k(z-h)e^{-kr} \rho d\Theta d\rho dz}{\pi r^3} \quad (1)$$

with the geometry defined in Figure 1.

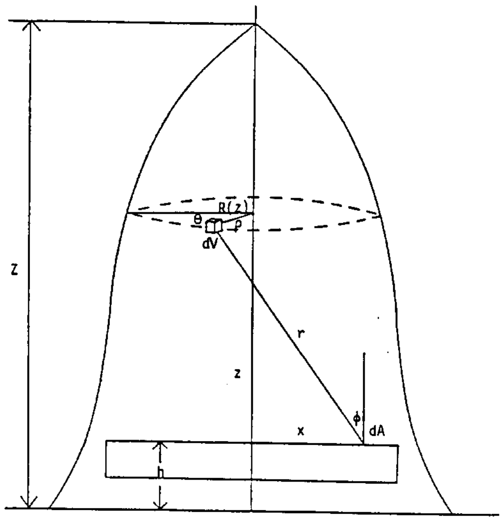


Figure 1. Geometry for Formulating the Radiative Interchange Factor Between a Pool Fire and a Horizontal Surface on a Tank Car Within the Fire.

The vector r between the element of gas volume and the surface can be determined as

$$r = (x^2 + \rho^2 + 2\, x\, \rho \cos \Theta + (z-h)^2)^{1/2} \quad (2)$$

The radius of the pool fire as a function of height was determined from experimental data (8) as

$R(z) = a_0 + a_1 z + a_2 z^2 + a_3 z^3 + a_4 z^4$

with

$a_0 = 2.24$ m $\qquad a_1 = -0.3806$

$a_2 = 0.6202 \times 10^{-1}\ m^{-1}$ $\qquad a_3 = 0.1219 \times 10^{-1}\ m^{-2}$

$a_4 = -0.3706 \times 10^{-2}\ m^{-3}$ (3)

The triple integral of Equation (1) was solved numerically. The solution is presented in Figure 2.

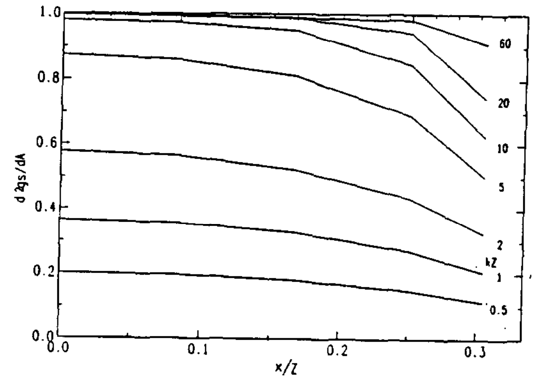


Figure 2. Radiative Interchange Factor Between a Pool Fire of Height Z and a Horizontal Surface on a Tank Car Within the Fire for Various Absorption Coefficients k. Diameter to Height Ratio of Pool Fire = 0.75, Height of Cylinder to Height of Pool Fire Ratio = 0.15.

The radiative interchange factor between a combined pool fire and a turbulent flame jet and a horizontal surface within the pool fire can be determined from the triple integral

$$\frac{d^2qs}{dA} = \int_h^Z \int_0^{Rad} \int_0^{\pi} \frac{2k_e z\,(e^{-k_a s})\,\rho d\theta d\rho dz}{\pi r^3} \qquad (4)$$

with the geometry defined in Figure 3.

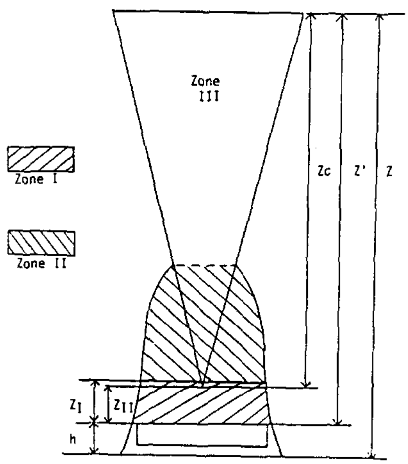


Figure 3. Geometry for Formulating the Radiative Interchange Factor Between a Pool Fire and Flame Jet and a Horizontal Surface on a Tank Car Within the Fire.

The quantities in the above equation are:

s = length of absorbing path

k_e = absorption coefficient of the emitting gas

k_a = absorption coefficient of the absorbing gas

The quantities in the three zones are given as

In Zone I,

Rad = radius of the pool fire (Equation 3)

k_e = k_p, $k_a = k_p$, $s = r = (x^2+\rho^2+2x\rho\cos\Theta+(z-h)^2)^{1/2}$

k_p = absorption coefficient of the pool fire gas

In Zone II

Rad = radius of the pool fire

k_e = k_p, if dV is in the pool fire region

k_e = k_c, if dV is in the cone jet region

$k_a s$ = $k_p s_p + k_c s_c$

s_p = the total absorbing path length inside the pool fire

s_c = the absorbing path length inside the cone jet

k_c = absorption coefficient of the cone jet gas

If the element of gas volume dV is at

1) $\rho \leq$ radius of cone, radius of cone = az_c, a = slope of cone

s_c can be calculated from the relation.

$$s_c = r\left(1 - \frac{x(x+\rho\cos\Theta) - a^2 z' Z_{II} - \sqrt{\rho^2(a^2 Z_{II}^2 - x^2\sin^2\Theta) - 2xa^2 Z_{II}\rho\cos\Theta(z' - Z_{II}) + a^2x^2(z' - Z_{II})^2}}{u^2 - a^2(z')^2}\right) \quad (5)$$

$$u^2 = x^2 + \rho^2 + 2x\rho\cos\Theta \quad (6)$$

$$s_p = r - s_c$$

2) $\rho >$ radius of cone,

2-a) $x \leq aZ_{II}$

$s_p = r$, $s_c = 0.0$

2-b) $x > aZ_{II}$

ρ_1 and Θ_1 must be determined first.

When dV is at $\Theta = 0$, ρ_1 is the radial distance from the axis of the cone at which the vector r will only touch the apex of the cone to reach the horizontal surface dA.

Θ_1 is the maximum angle at which the vector r will touch the surface of the cone at one point to reach the horizontal surface dA.

$$\rho_1 = \frac{x(z' - Z_{II})}{Z_{II}} \quad (7)$$

$$\Theta_1 = \cos^{-1}\left(\frac{a^2 Z_{II} z_c + \sqrt{(x^2 - a^2 Z_{II}^2)(\rho^2 - a^2 z_c^2)}}{x\ \rho}\right) \quad (8)$$

If $\rho \geq \rho_1$, for any Θ, $s_p = r$, $s_c = 0.0$

If cone radius $< \rho < \rho_1$, and $\Theta \geq \Theta_1$,

$$s_p = r,\ s_c = 0.0$$

If cone radius $< \rho < \rho_1$, and $\Theta < \Theta_1$, $s_p = s_1 + s_3$

s_1 = the absorbing path length from dV in the pool fire to the surface of the cone; it can be evaluated from the following relation,

$$s_1 = r\left(1 - \frac{x(x+\rho\cos\Theta) - a^2 z' Z_{II} + \sqrt{\rho^2(a^2 Z_{II}^2 - x^2\sin^2\Theta) - 2xa^2 Z_{II}\rho\cos\Theta(z' - Z_{II}) + a^2x^2(z' - Z_{II})^2}}{u^2 - a^2(z')^2}\right) \quad (9)$$

$$u^2 = x^2 + \rho^2 + 2x\rho\cos\Theta$$

S_c = the absorbing path length inside the cone jet; it can be evaluated from Equation (5), with Θ, ρ, z' in Equation (5) which describe the location of the entry point to the cone, given as Θ_2, ρ_2, z'_2 in Equations (10)-(12).

$$z'_2 = z' \left(1 - \frac{s_1}{r}\right) \quad (10)$$

$$\rho_2 = a(z'_2 - Z_{II}) \quad (11)$$

$$\Theta_2 = \sin^{-1}\left(\frac{\rho \sin\Theta\,(1 - \frac{s_1}{r})}{\rho_2}\right) \quad (12)$$

s_3 = the absorbing path length from the exit point of the cone to the element of area dA on the horizontal surface

$$s_3 = r - s_1 - s_c$$

In Zone III,

Rad = radius of the cone

$k_e = k_c$

$k_a s = k_p s_p + k_c s_c$

s_c = the absorbing path length inside the cone

s_c can be evaluated from Equation (5).

s_p = the absorbing path length inside the pool fire

If the exit point from the cone is in Zone II,

$$s_p = r - s_c$$

Otherwise, s_p can be calculated by trial and error by equating the following two equations,

$$R' = \sqrt{x^2 - \frac{s_p}{r}(2x(x+\rho\cos\Theta)) + \left(\frac{s_p}{r}\right)^2 (x^2+\rho^2+2x\rho\cos\Theta)} \quad (13)$$

$$R' = a_0 + a_1 \left(\frac{s_p}{r} z' + h\right) + a_2 \left(\frac{s_p}{r} z' + h\right)^2 + a_3 \left(\frac{s_p}{r} z' + h\right)^3 + a_4\left(\frac{s_p}{r} z' + h\right)^4 \quad (14)$$

$z' = z-h$

a_0, a_1, a_2, a_3, a_4 are given by (3).

A comparison of the radiative interchange factors between the flames and a horizontal surface within the pool fire with and without the turbulent diffusion flame present are given in Table I for conditions likely to exist after an accident. The calculations demonstrate the radiative contribution by the turbulent diffusion flame jet is negligible.

Table I

Comparison of Interchange Factors Between Pool Fire and Horizontal Surface in Presence and Absence of Turbulent Flame Jet

x meters	No Turbulent Flame Jet	Turbulent Flame Jet	k_p m^{-1}	k_c m^{-1}
.26	0.99244	0.99281	3.28	3.28
.5	0.99083	0.99120		
1.0	0.98612	0.98648		
1.5	0.94149	0.94184		
1.83	0.74337	0.74373		
.26	0.99427	0.99477	9.84	3.28
.5	0.99354	0.99404		
1.0	0.98702	0.98751		
1.5	0.98035	0.98084		
1.83	0.90843	0.90888		

Experimental Results

A calorimeter was constructed as shown in Figure 4. It consisted of cylindrical test section with one half the cylinder as a channel and the other half divided into four equal channels. Each of the walls between the channels was insulated to prevent heat transfer between the five separate channels. The five channels were assembled and held together by a plate fixed at each end. The outside diameter of the cylinder was 76 mm.

A thermocouple was installed at each end of each channel in order to measure the temperature rise of the water flowing through the channel. The flow rate of the water through each channel was measured with a rotameter. The test section was 457 mm in length. Both ends of the cylinder leading to the test section were water cooled by an annular flow cooling section built into the cylinder.

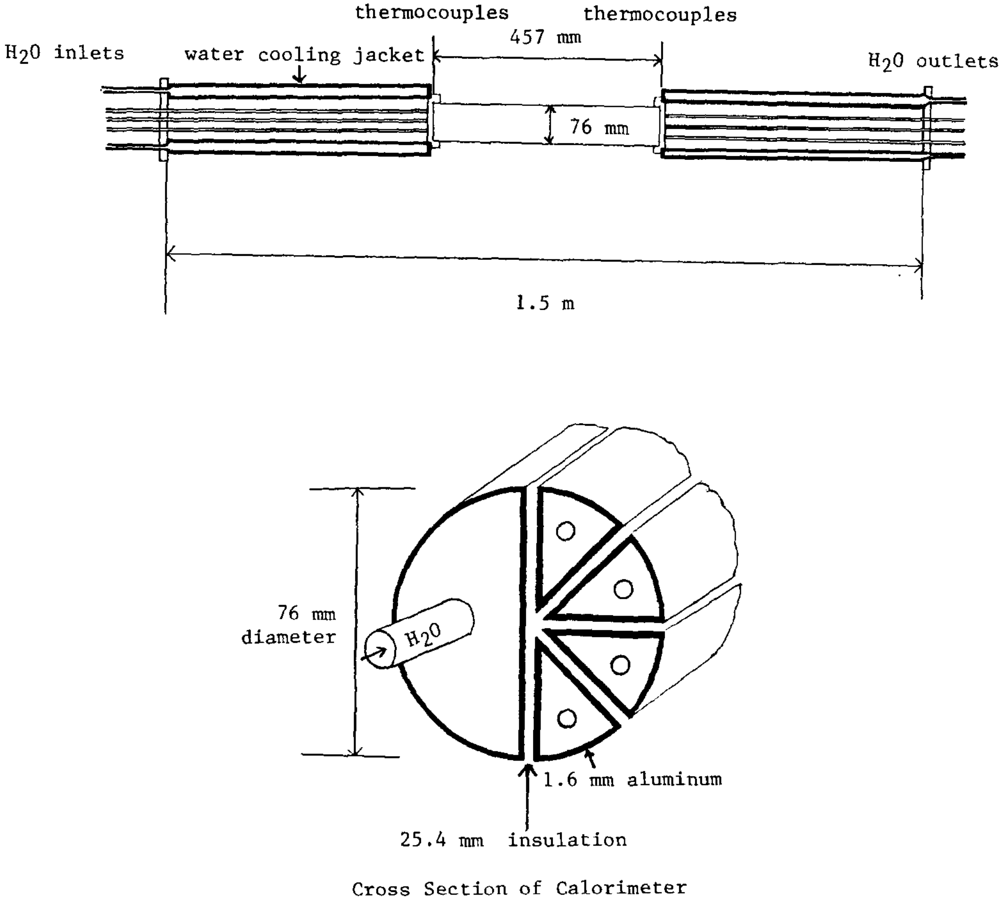
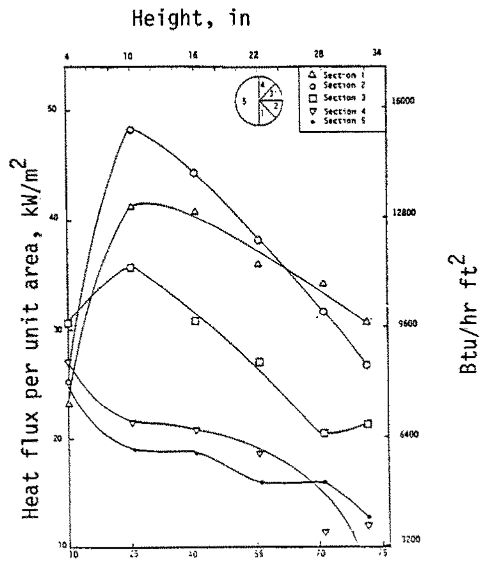


Figure 4. Calorimeter Used to Collect Data on Heat Flux to a Cylinder Engulfed in a Pool Fire With and Without a Turbulent Flame Jet.

The calorimeter was placed at various positions in a propanol pool fire with and without a high velocity turbulent jet operating next to the cylinder. Typical results of these experiments are shown in Figures 5-7 and Table II.

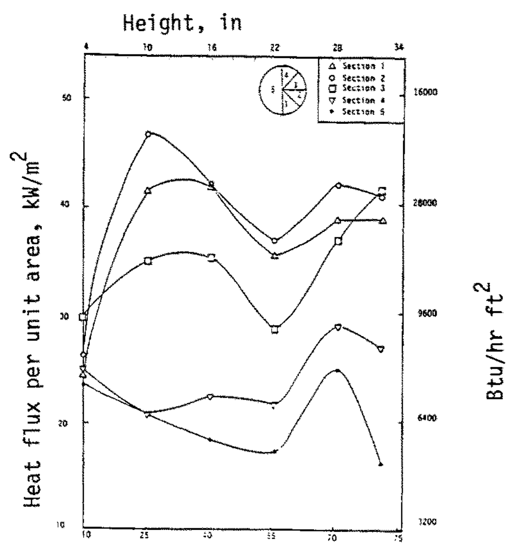
Figure 5 presents the heat flux per unit area to the various test channels vs the height of the top surface of the cylinder above the fuel surface when the test section of the calorimeter was engulfed in a pool fire. The calorimeter was off-centered by 40 mm.



Height (From the Fuel Surface to the Top of the Calorimeter), cm

Figure 5. Heat Flux per Unit Area on a Cylinder Section vs Height for a Cylinder Engulfed in a Propanol Pool Fire.

Figure 6 presents the same diagram with the same experimental arrangement except the propane jet flame was operating. The 4 channel half of the test section was next to the propane jet flame.



Height (From the Fuel Surface to the Top of the Calorimeter), cm

Figure 6. Heat Flux per Unit Area on a Cylinder Section vs Height for a Cylinder Engulfed in a Propanol Pool Fire with a Turbulent Propane Flare Present.

The results are compared directly in Table II for the pool fire alone and the pool fire plus turbulent flame. Also presented are readings of a radimeter placed with its sensing surface at about the same height as the test cylinder upper surface. The comparison is for the test cylinder in its lowest position, 100 mm.

Table II

Comparison of Heat Fluxes To Cylinder
With and Without Propane Flare

	Heat Flux kW/m^2 Section 4	Section 5	Radiometer
Pool Fire	24.9	23.5	23.2
Pool Fire + Flare	27.2	24.9	24.5
% Difference	9.0	5.6	5.5

Height of Top Surface of Calorimeter
Test Section Above Fuel Surface 100 mm.

The results indicate that the increase in heat transfer to the cylinder due to the turbulent jet flame is small, less than 10%.

A set of experiments were carried out with the test section of the cylinder engulfed in a pool fire and placed directly in the path of the turbulent jet so that the test section encountered direct impingement. The results for this test at a cylinder height above the jet of 710 mm is presented in Figure 7. The heat flux per unit area increased substantially to all channels with the percent increase being between 60 and 271%.

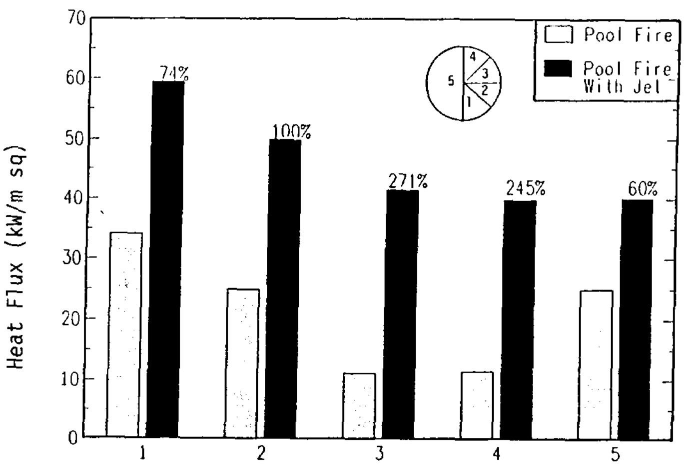


Figure 7. Heat Flux per Unit Area on a Cylinder Section Engulfed in a Propanol Pool Fire with a Turbulent Propane Flare Impinging on the Cylinder. Height of Top Surface of Cylinder Above Turbulent Jet 710 mm.

Conclusions

1) The radiative interchange factor between a pool fire and a horizontal surface within the pool fire has been evaluated.
2) The radiative interchange factor between a pool fire and a turbulent diffusion flame jet emerging from the pool fire and a horizontal surface within the pool fire has been evaluated. The presence of the turbulent diffusion jet flame makes only a small difference in the result for conditions likely to occur in a tank car accident.
3) Experimental data indicate that the presence of a turbulent flame jet does not significantly effect the rate of heat transfer to a horizontal cylinder immersed in a pool fire unless the flame jet is impinging directly on the cylinder. This case gives a significantly higher heat flux to the cylinder and represents the most severe situation for a tank car exposed to a fire.

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