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COMPUTER MODELLING OF HEAT RADIATION FROM SEVERAL EMITTERS WITH APPLICATIONS

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ABSTRACT

Computer program has been created to calculate intensity of heat radiation impressed onto the receptors of orientation corresponding to maximum heat flow values. The program allows for up to 20 rectangular emitters for each of three orthogonal orientations. This software has proved to be useful for performance based verification of the likelihood of fire spread between adjacent buildings. The application of verification method CV1 of the Building Code of Australia is discussed in detail.

1. SOFTWARE

Calculation of the intensity of heat radiation from several sources is one of standard fire engineering tasks. Analytical expressions for configuration factors are very cumbersome. Hence, creation of a user friendly aid to compute the intensity of heat radiation suitable for complex configurations is an important issue. This paper describes a theoretical background of program RADIATION which is one of the modules of the Fire Engineering package FIREWIND created by Fire Modelling & Computing.

The program computes the intensity of heat radiation from a set of rectangular emitters of three orthogonal orientations. Up to 20 emitters of each orientation are allowed.

The receptor which is of interest is usually an opening of a building adjacent to a building on fire. However, a combustible item, for instance, a curtain, can have orientation quite different from the plane of this opening. Hence, it is of interest to find the heat flux impressed on a receptor of such an orientation which corresponds to the maximum heat flow.

The calculations performed by the program follow the expression of the configuration factor C_f in the form presented in Ref. [1] which can be shortly written as following:

$$C_f = P \cos \alpha + Q \cos \beta + R \cos \gamma \qquad (1)$$

The explicit expressions for P, Q and R are reproduced in Appendix. α, β and γ are the angles between the normal to the receptor and three rectangular coordinate axes X, Y and Z accordingly. Equation (1) defines configuration factor C_f as a projection of a vector with components P, Q and R on the normal to the receptor. The orientation of the receptor with the maximum configuration factor is the orientation of the vector {P, Q, R}. The largest configuration factor from one emitter is:

$$C_{max} = \sqrt{P^2 + Q^2 + R^2} \qquad (2)$$

The receptor where the maximum heat flux is impressed does not necessarily coincide with the plane of the receptor window (see Fig. 1). For several emitters the component vectors are subject to summation upon the rules of the vector analysis. However, there is more to this than just application of vector formulae. Namely, at certain orientations of the maximum heat flux some of the emitters might not be seen. The example illustrating this situation is shown in Fig. 2. Hence, program RADIATION examines all possible combinations of the emitters seen at any point of observation, to find the maximum configuration factor. This algorithm for N emitters is shown schematically in Fig. 3. Components 1 to n are those which contribute to the maximum of the configuration factor. Components n + 1 to N are disregarded. The maximum configuration factor is for a receptor perpendicular to vector S which is a sum of components 1 to n. It can be seen that emitters 1 to n are seen from the receptor of the maximum configuration factor, because the angles between the component vectors and the normal to the receptor are obtuse. The angles between the disregarded components and the normal are acute, and the corresponding emitters are not seen from the receptor of the maximum configuration factor.

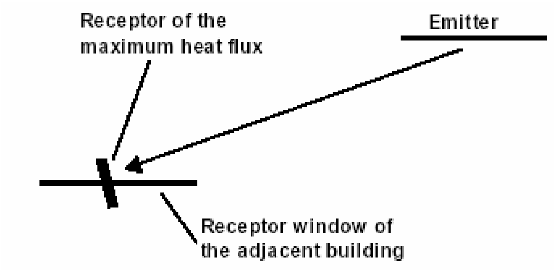


Fig. 1: Receptor and emitter located at an acute angle to each other

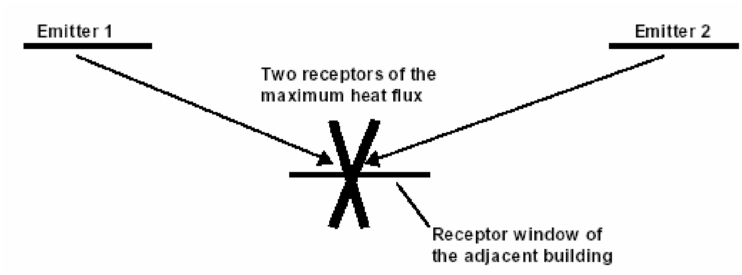


Fig. 2: Receptor window between two emitters

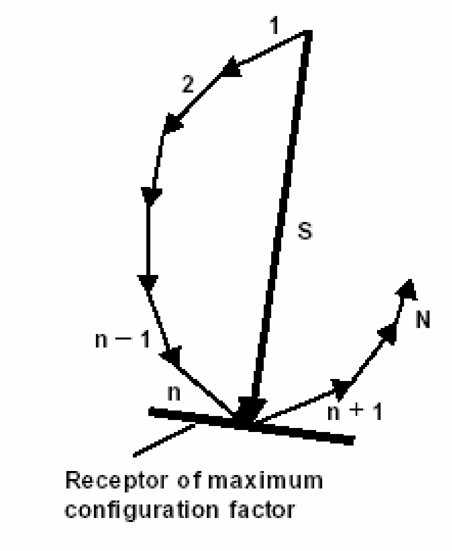


Fig. 3: Heat radiation from several emitters onto a receptor of the maximum configuration factor

Program RADIATION computes the maximum heat flow at the point of observation and finds the orientation of the receptor of maximum heat flow. It also computes maximum heat fluxes in the vicinity of the point of observation and presents the results of calculations as a table of maximum values and as a "radiation map". The radiation map is built in a square-shaped domain in a plane normal to one of three chosen coordinate axes.

Program RADIATION allows to vary the temperature and emissivity of the emitters, but does not calculate the radiation from the receptor.

It should be noted that the intensities of the heat flux computed by the program are not additive, because the heat fluxes computed for different combinations of the emitters may be obtained for the receptor planes of different orientations.

Examples of the print-outs of program RADIATION are shown in Figs. 4 and 5. The print-outs include also entries to the program.

Program Radiation

RADIATION
at a given point
from a system of fire sources

(all dimensions are in meters)

X-sources:
Radiation temperature 1000°C

Distance	Offset		Size of source		Opening
X	Yx	Zx	Y	Z	%
16	-3	0	3	1.8	100
14	3	0	3	1.8	100

Z-sources:
Radiation temperature 1000°C

Distance	Offset		Size of source		Opening
Z	Xz	Yz	X	Y	%
10	5	7	10	14	100

Radiation flow at point P 28.37 kW/m²

Fig. 4: Print-out of program RADIATION for one observation point

Program Radiation

(All dimensions are in meters)

X-sources:

Radiation temperature 1000°C

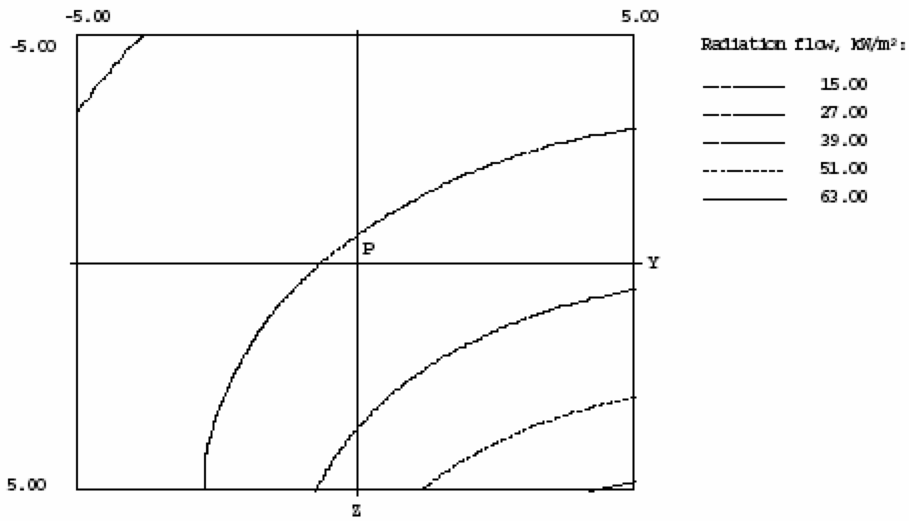
Distance	Offset		Size of source		Opening
X	Yx	Zx	Y	Z	%
16	-3	0	3	1.8	100
14	3	0	3	1.8	100

Z-sources:

Radiation temperature 1000°C

Distance	Offset		Size of source		Opening
Z	Xz	Yz	X	Y	%
10	5	7	10	14	100

RADIATION MAP YZ



Nodal radiation data, kW/m²:

Z \ Y	-5.00	-2.50	0.00	2.50	5.00
-5.00	13.72	16.35	18.85	20.89	22.12
-2.50	15.55	19.28	23.03	26.18	28.14
0.00	17.22	22.60	28.37	33.38	36.53
2.50	18.20	26.01	35.24	43.42	48.37
5.00	17.19	28.19	43.86	57.64	64.68

Orientation of maximum radiation flow

at point P(0,0,0): $\theta = 35.0°$, $\varphi = 44.7°$

Fig. 5: Print-out of program RADIATION – Radiation map in the vicinity of observation point P

2. APPLICATIONS

The program does not allow to take into account shading of radiation by objects between emitters and receptors, neither re-radiation from the adjacent surfaces. Hence, caution should be exercised in attempting to apply this software to radiation inside compartments where these effects are significant. Program RADIATION is applicable to scenarios where considerable re-radiation does not occur.

One of the most useful applications of the program is in radiant heat assessments of mutual exposure of two adjacent buildings across a boundary. In these studies radiation from openings of one building onto openings of another building is calculated. Examples of such application are discussed below on the basis of the writer's experience in Australia.

According to the prescriptive requirements of the Building Code of Australia (BCA), openings are deemed to be safe, if they are located at a distance of 3 m from a side or rear boundary or at a distance from an adjacent building of 6 m at parallel orientation and 4 m at perpendicular orientation. A closer situation is subject to engineering analysis.

The BCA offers two verification methods named CV1 and CV2 for this analysis. Method CV1 exercises a generic approach, considering only distance from the boundary irrespective of the design of a building on the opposite side of the boundary. Method CV2 is related to the mutual exposure of two buildings on the same allotment. Both methods specify only distances between the building and a boundary or another building and ignore offsets of the openings. Of these methods, CV1 is the most useful, because considering mutual exposure of two buildings one normally can be much more specific, taking into account the exact location of the openings. Hence, here we concentrate on verification method CV1.

Method CV1 requires the building not to create the heat flux at the boundary and behind the boundary in excess of that specified in Table 1, and also to withstand the heat flux specified in this table, depending on the distance from the boundary.

Table 1: Limiting values of heat flux, CV1 verification method of the BCA [2]

	Heat flux, kWm^{-2}
On boundary	80
1 m from boundary	40
3 m from boundary	20
6 m from boundary	10

To use this table, the necessity in the software computing the heat flux is immediate. All the calculations below have been performed using program RADIATION.

The first condition of CV1 called CV1(a), not to impress an excessive heat radiation onto the boundary and behind the boundary, is easy to satisfy. For instance, an emitter with radiation temperature 1000°C, 6 m wide and 3 m high located at 3 m from the boundary is already within the limits. This condition is considered to be too lenient, because it allows to impress 20 kWm^{-2} onto windows located at a distance of 3 m from the boundary, which is a safe distance upon the prescriptive requirements, and are consequently not protected.

The immediate question is – what radiation temperature to use. The BCA does not specify any, leaving this to a fire engineer. Approved Document B which is in force in England [3] recommends to use for shops and commercial buildings radiation intensity of 168 kWm^{-2}, which corresponds to the radiation temperature of 1040°C, and 84 kWm^{-2}, corresponding temperature 830°C, for residential, office, assembly and recreational buildings. According to the information from IAFSS forum in Internet [4], in New Zealand the radiation temperature is assumed to depend on the fire load as shown in Table 2.

Table 2: Assumed dependence of radiation temperature on fire load [4]

Fire load, MJm^{-2}	Intensity of radiation, kWm^{-2}	Radiation temperature, °C
0 – 500	88	840
501 – 1000	108	900
> 1000	153	1010

This approach is considered to be preferable.

It is worth mentioning for completeness that while using CV1(a), the height of the emitter has to be assumed with the account of leaping flames, usually 25% in excess of the geometrical height of the opening.

Typically, verification method CV1(a) needs not be used for buildings protected by sprinklers. It can be shown by modelling of compartment fires that the temperature of a hot layer in a sprinkler protected compartment will be below the level that can cause fire spread by heat radiation.

The condition of CV1 to withstand certain intensity of heat radiation called CV1(b) is much more demanding. In the first instance, it is not satisfied for openings that are located at a distance of 3 m and are deemed to be safe, because a non-protected opening would not withstand the flux of 20 kWm^{-2}.

The BCA does not specify what is considered to be a safe flux which an opening may withstand. According to the advice of Ref. [5], for piloted ignition the criterion of 12.5 kWm^{-2} is used in many countries. However, based on tests conducted in Sweden and Finland in 1970's, the Swedish regulations have adopted the criterion of 15 kWm^{-2}.

For the non-piloted (spontaneous) ignition it seems to be reasonable to accept as a criterion a limit for non-piloted ignition of cotton fabric after a long time, which is 27 kWm^{-2} [6].

The large difference between the limits for piloted and spontaneous ignition is utilised in Australia to protect windows located close to the boundary against piloted ignition only, i.e. to allow the windows to be openable, but to prevent sparks and debris to enter the building. Namely, stainless steel mesh screens are installed in metal frames fixed permanently on top of sliding windows. The screens that are used are manufactured of 0.8 mm wire with 10 threads per inch. They are black coated, to prevent glaring which might impair the vision from inside of the building. Such screens have been tested [7] and were found to reduce the transmitted heat flux approximately 40%. With these screens, the windows can be deemed to withstand a heat flow of approximately 27/0.6 = 45 kWm^{-2}. In the events when windows are situated at an angle to the boundary the allowed heat flux might be still larger, because the effective gaps between the wires are smaller and effective distance to a fire source is longer, as shown in Fig. 6.

The difficulty in using CV1(b) is to apply it to openings located at various distances from the boundary, whereas the BCA specifies the limits for several discrete distances. Hence, for practical applications Table 1 should be interpolated. The most appropriate equation for interpolation of CV1 is logarithmic, because where heat flux values differ by a multiplier of 2, the differences of logarithms will be the same in each interval of interpolation. The equation of interpolation is:

$$Y = a + bx + cx^2 + dx^3 \qquad (3)$$

$$Y = \log (F)$$

where x is a distance from the boundary, F is the heat flux, a, b, c and d are constants defined to match the numbers of Table 1:

a = 1.90309; b = -0.37127; c = 0.07693;
d = -0.00669.

The results of interpolation are shown in Fig. 7.

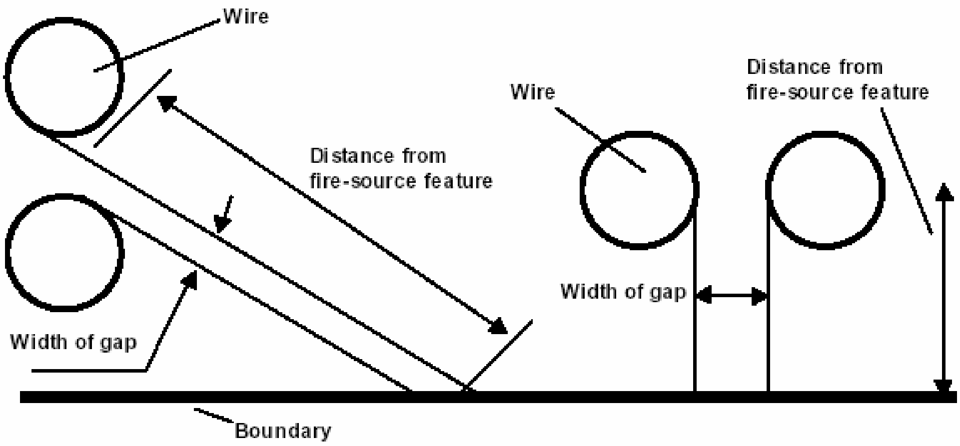


Fig. 6: Comparison of mesh perpendicular to the boundary and facing the boundary

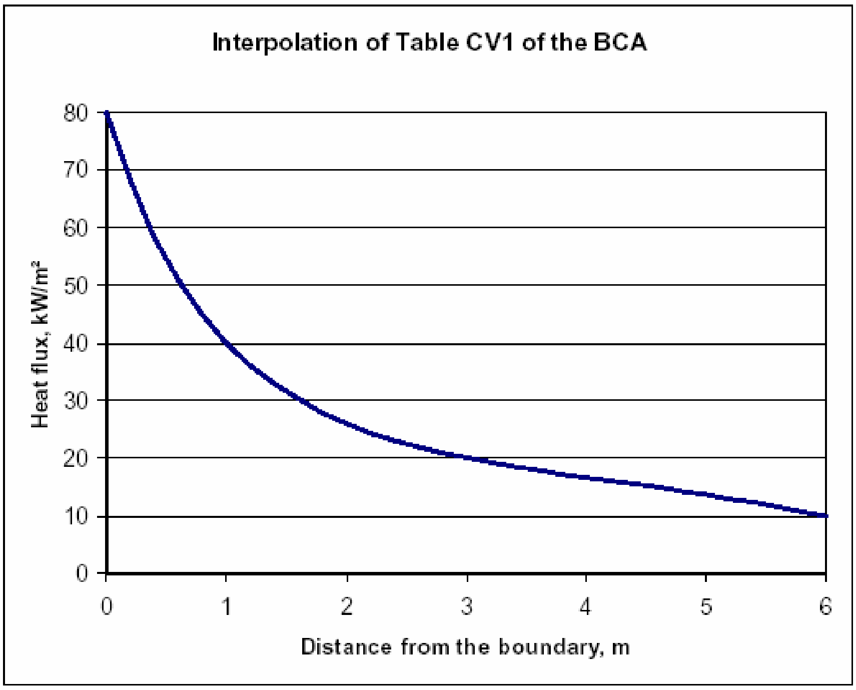


Fig. 7: Interpolation of Table CV1 of the BCA

However, this method is not always applicable. Consider, for instance, openings in the wall perpendicular to the side boundary and set back from the public road just at a short distance. It should be taken into account that openings of the adjacent building, whatever they are, will be exposed to the openings of the subject building only at a size of this setback, and no more. Then the maximum flux onto the wall perpendicular to the side boundary is smaller than that obtained by interpolation. To find this flux, verification method CV1(b) can be implemented using hypothetical heat radiation sources which are in correspondence with Table 1. It is difficult, if possible at all, to cover all the range of distances with one emitter. Hence, two emitters have been used in our practice, for instance, like those shown in Table 3.

The values of the maximum heat flux impressed by these emitters at the boundary and at the nominated distances from the boundary correspond to those in Table 1. Then calculations of the heat flux onto the window facing the public road will be carried out as shown in Fig. 8, with considerable alleviation compared with mindless use of CV1 figures. The choice of height of the hypothetical emitters is to some extent arbitrary, but it is considered that the height of 3 m is a conservative choice in most applications.

Verification method CV1 is an implementation of a generic approach where the goal is to avoid fire spread irrespective of what a building might be built across the boundary. However, in many cases one can rely on the longevity of the adjacent building and argue that no considerable redevelopment of the adjacent building is likely in a foreseeable future. In this instance a direct mapping of the computed intensities of heat radiation on the elevation of the adjacent building is a preferable approach.

In our opinion, to make verification method CV1 more useful, it should be modified. The most important is to change the recommended value for a distance of 3 m from the boundary. It should be brought in correspondence with the prescriptive provisions where 3 m from the boundary is deemed to be a safe distance. Hence, value of 15 kWm^{-2} should be used, and not 20 kWm^{-2}, as it is now. Other numbers of CV1 may also be corrected, but this is out of the scope of this paper.

Table 3: Hypothetical radiation sources for implementation of method CV1(b)

	Width, m	Height, m	Distance behind the boundary, m	Range of application from the boundary, m
Source 1	2.52	2.52	1.3	0 – 1
Source 2	5.17	3.00	2.56	1 – 3

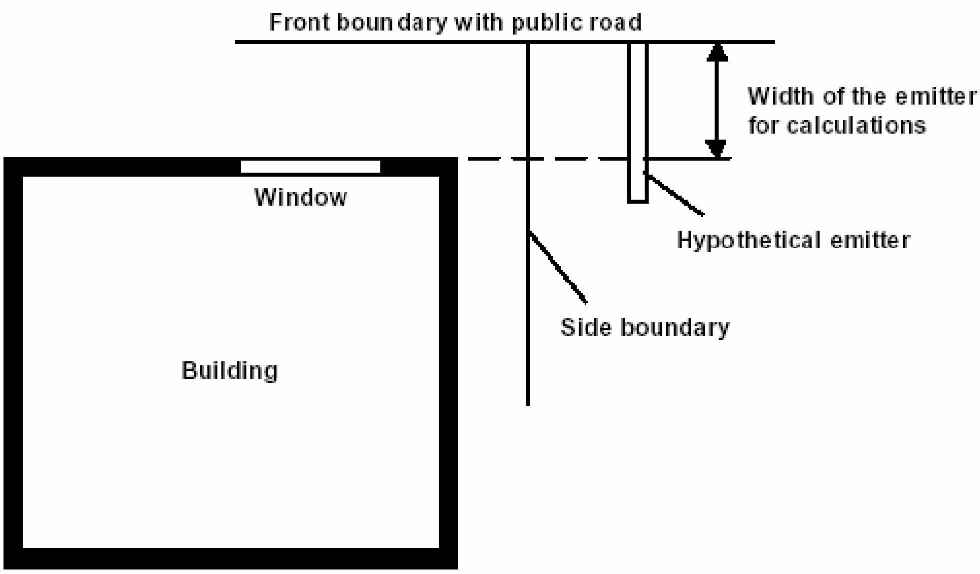


Fig. 8: Calculations of the heat flux from a hypothetical emitter onto a window facing public road

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APPENDIX

Configuration factor C_f is defined by equation:

$$F = C_f \varepsilon \sigma T^4$$

where F is the heat flow per unit area; ε is the emissivity of the emitter; σ is the Stefan-Boltzmann's constant; and T is the absolute temperature of the emitter.

Formulae to compute components of the configuration factor for the scenario: rectangular emitter located in plane y = 0 between coordinates x_1, x_2, z_1, z_2; infinitesimal receptor located at point x = z = 0 at a distance y_1 from the origin, are (see Ref. [1]):

$$Q = -\frac{Ax_1 + Bx_2 + Cz_1 + Dz_2}{2\pi}$$

$$P = \frac{(A-B)y_1}{2\pi}$$

$$R = \frac{(C-D)y_1}{2\pi}$$

where

$$A = \frac{1}{\sqrt{x_1^2 + y_1^2}}\left(\tan^{-1}\frac{z_2}{\sqrt{x_1^2 + y_1^2}} + \tan^{-1}\frac{z_1}{\sqrt{x_1^2 + y_1^2}}\right)$$

$$B = \frac{1}{\sqrt{x_2^2 + y_1^2}}\left(\tan^{-1}\frac{z_2}{\sqrt{x_2^2 + y_1^2}} + \tan^{-1}\frac{z_1}{\sqrt{x_2^2 + y_1^2}}\right)$$

$$C = \frac{1}{\sqrt{z_1^2 + y_1^2}}\left(\tan^{-1}\frac{x_2}{\sqrt{z_1^2 + y_1^2}} + \tan^{-1}\frac{x_1}{\sqrt{z_1^2 + y_1^2}}\right)$$

$$D = \frac{1}{\sqrt{z_2^2 + y_1^2}}\left(\tan^{-1}\frac{x_2}{\sqrt{z_2^2 + y_1^2}} + \tan^{-1}\frac{x_1}{\sqrt{z_2^2 + y_1^2}}\right)$$