

Mathematical Models for Wind-Aided Flame Spread of Floor Coverings

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ABSTRACT

Recently the fire hazard of floor coverings in a wind-aided flame spread scenario was shown in an extensive series of full scale and small scale tests. This paper describes two types of mathematical models used in this work for the prediction of wind-aided flame spread on floor coverings. Both models use cone calorimeter data as input. The first model gives the analytical solution for the flame spread as a function of time. This model can be used for a specific scenario and gives a good estimate of the possible risk of the floor covering. The second model is a numerical simulation model which allows the user to calculate the flame spread in a wider range of situations. This model can be used in the future for implementation in zone- or field models as input for the growth of the fire as a function of time. Both models show an acceptable degree of prediction level of the available full scale test results for floor coverings in a room corridor scenario. These full scale test results comprise most known families of floor coverings.

KEY WORDS: mathematical modelling, floor covering, wind-aided flame spread, heat release, cone calorimeter

INTRODUCTION

As mathematical modelling of fire phenomena gains importance, it has been used in ever increasing numbers of applications [1]. Up till recently only limited work has been done in applying this approach to commercially available floor coverings. Successful modelling of upward flame spread in wall linings, however, prompted an in-depth experimental and theoretical study of flame spread of floor coverings. The experimental data found in reference

[2] has provided the basis for the development of two types of mathematical models of flame spread of floor coverings. The results of small scale tests have been used as input with an acceptable level of prediction of large scale results. These two mathematical models will be presented in this paper while an overview of related work is presented in reference [3]. Figure 1 shows how these models have been used in a flow diagram approach to research the risk assessment of wind-aided flame spread on floor coverings.

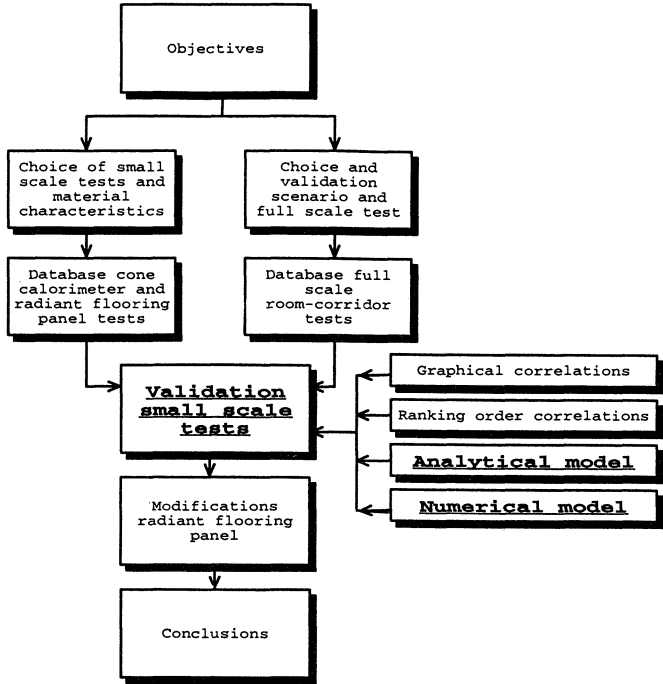


FIGURE 1: Position of the mathematical models within the research of wind-aided flame spread of floor coverings.

ANALYTICAL MODEL FOR WIND-AIDED FLAME SPREAD OF FLOOR COVERINGS

Description

This model will result in the pyrolysis distance as a function of time for a wind-aided configuration. A similar approach has been performed for the upward flame spread of wall linings [4], [5], [6]. Until now this approach has not been applied to horizontal wind-aided flame spread on a wide range of floor coverings in a room corridor scenario. Figure 2 shows a schematic picture of the geometry of this model.

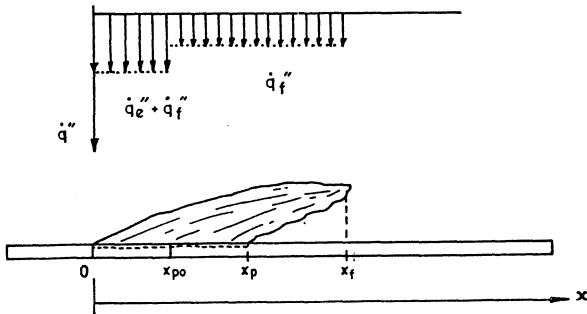


FIGURE 2: Description of horizontal wind-aided flame spread.

The following assumptions are made in this analytical model :

- (i) The material is considered to be thermally thick.
- (ii) The heat flux of the flame, \dot{q}_f'' , is constant for the area $x \leq x_f$ and zero for $x > x_f$.
- (iii) The heat flux of the thermal attack, \dot{q}_e'' , is constant for the area $0 < x < x_{po}$. In this area the material will ignite after a time equal to the ignition time at a uniform heat flux \dot{q}_e'' .
- (iv) Radiation from the hot smoke gases is included in the thermal attack for the area $0 < x < x_{po}$, equal to the distance of floor coverings in the room.
- (v) Between the heat release and the length of the flame, the following linear relationship can be used:

$$\frac{x_f}{x_p} = k_f \dot{E}'' \quad (1)$$

- (vi) The amount of combustible flooring material is limited with the exception of some wooden floor coverings. Hence it is necessary to take into account an extinction time of the material due to the fact that all material will be consumed after a time defined as t_{bo} . So the solution of the problem is divided into two periods.

For flame spread of floor coverings, the heat flux of the thermal attack, \dot{q}_e'' , in a real situation is mainly the radiation from the hot smoke gases under the ceiling. Assumption (iv) takes into account the fact that the heat flux of the thermal attack is limited to the area in the room covered with floor covering. Hence one can determine the moment the floor covering in the room ignites and whether there is flame spread towards the end of the corridor.

The constant cited in equation (1) is the flame length factor. In the literature an empirically determined value of $k_f = 0.01 \text{ m}^2/\text{kW}$ is assumed for a linear relationship [6] in case of vertical flame spread. Although for the horizontal orientation the value might depend on the angle between the flame and the floor covering, we will use this value of k_f as a worst case calculation. The first period defined in assumption (vi) is from time zero until the moment

that the material which ignited in the initial area (distance x_{p0}) is extinguished ($0 < t < t_{b0}$). The pyrolysis front speed for this period can be written as [4]:

$$\frac{dx_p}{dt} \equiv \frac{x_p(t + t_{ig}) - x_p(t)}{t_{ig}} = \frac{x_f(t) - x_p(t)}{t_{ig}} \quad (2)$$

where t_{ig} is equal to the ignition time of the material determined for example in the cone calorimeter at 25 or 35 kW/m². The second period starts when the initial surface is extinguished ($t > t_{b0}$). For this case the net increase of the pyrolysis can be calculated as the difference between the velocity of the pyrolysis front ($v_p(t)$) and the velocity of the extinction front ($v_b(t)$) [4]:

$$v_p(t) - v_b(t) = \frac{d}{dt}(x_p - x_b) = \left(\frac{x_f(t) - x_p(t)}{t_{ig}} \right) - \left(\frac{x_p(t) - x_b(t)}{t_{b0}} \right) \quad (3)$$

The extinction time t_{b0} is also determined by means of small scale data, namely the cone calorimeter. Considering these two periods the analytical solution then becomes :

1) For $0 < t < t_{b0}$

Inserting equation (1) into equation (2) yields:

$$\frac{dx_p}{dt} = (k_f \dot{E}'' - I) \frac{x_p}{t_{ig}} \quad (4)$$

This equation can be integrated using the initial condition that at $t = 0$, $x_p = x_{p0}$. The solution is then :

$$x_p = x_{p0} \exp\left[\frac{(k_f \dot{E}'' - I)t}{t_{ig}}\right] \quad (5)$$

Thus, the flame spread will accelerate if $k_f \dot{E}'' > 1$ which implies that above a certain heat release acceleration will occur.

2) For $t > t_{b0}$

In this case the non-dimensional flame length is equal to:

$$\left(\frac{x_f - x_b}{x_p - x_b} \right) = k_f \dot{E}'' \quad (6)$$

Combining equations (3) and (6) one obtains:

$$\frac{d}{dt}(x_p - x_b) = (x_p - x_b) \left[\frac{(k_f \dot{E}'' - I) \cdot t_{b0} - t_{ig}}{t_{ig} \cdot t_{b0}} \right] \quad (7)$$

This equation can be integrated using the initial condition that for $t=t_{b0}$, $(x_p-x_b) = (x_{pl} - x_{p0})$. The length of the pyrolysis zone then becomes:

$$(x_p - x_b) = (x_{pl} - x_{p0}) \exp\left[\left(k_f \dot{E}'' \cdot \frac{t_{ig}}{t_{b0}} - I\right) \frac{(t - t_{b0})}{t_{ig}}\right] \quad (8)$$

and the risk for an acceleration of the flame spread depends now on three factors:

a) the normalised flame length, $\frac{(x_f - x_b)}{(x_p - x_b)}$, given by (6) which is a linear function of \dot{E}'' ;

b) the ignition time, t_{ig} ;

c) the burning time of the material, t_{b0} .

If $\left(k_f \dot{E}'' - \frac{t_{ig}}{t_{b0}}\right) > 1$, then the flame spread will accelerate otherwise the extinction front will catch the pyrolysis front and the floor covering will extinguish.

Results and discussion

To apply the analytical expression determined above we need three parameters. We will use the following values:

- To determine the flame height, the average rate of heat release (AHRR) in the cone calorimeter is used for \dot{E}'' . The value for k_f is taken as $0.01 \text{ m}^2/\text{kW}$ being the most severe condition. If necessary this value can be adopted as a function of the angle between flame and surface.
 - The ignition time in the cone calorimeter is chosen at a certain heat flux level for t_{ig} .
 - The burning time in the cone calorimeter is chosen at a certain heat flux level for t_{bo} .
- An overview of these parameters is summarised in table 1 for flux levels of 25 kW/m^2 and 35 kW/m^2 . The shaded areas denote values greater than 1, an ‘*’ corresponds to no ignition, C_i represents the exponent in equation (5), and C_b the exponent in equation (8).

Material	C_i 25 kW/m ²	C_b 25 kW/m ²	C_i 35 kW/m ²	C_b 35 kW/m ²
PVC 1	*	*	0.4500	- 0.0175
PVC 2	1.1900	0.7015	1.0100	0.6531
PVC 3	0.8600	0.7002	0.9300	0.8412
PVC 4	0.8800	0.6230	1.1100	0.9188
PVC 5	0.8700	0.5181	0.9900	0.7836
Linoleum	1.6900	1.0794	1.9200	1.5490
Parquet 1	0.7500	0.4789	1.1100	0.9807
Parquet 2	0.6300	0.4934	0.8200	0.7581
Parquet 3	1.2400	0.7125	1.6700	1.2506
Cork FR	0.4300	0.3023	0.6400	0.6080
Carpet 1	1.3100	0.3018	2.0100	1.6518
Carpet 2	1.3200	- 1.5467	1.9500	1.3884
Carpet 3	0.4300	0.1116	1.1500	1.0278
Carpet 4	1.6900	1.1584	2.4200	2.1758
Carpet 5	1.7000	0.6946	2.2500	1.8237
Carpet 6	1.4900	1.0242	1.9700	1.8217
Rubber	0.7500	0.2621	0.9600	0.7308

For a heat flux level of 25 kW/m^2 , 8 materials have $C_i > 1$. All materials causing flashover are included in these 8 as can be seen in figure 3. Figure 3 gives a graphical overview for this parameter indicating at the same time the materials causing flashover (represented by the black boxes). Only PVC 2 and Carpet 1 are expected to show an increasing flame front in contradiction to the full scale tests [2]. However most floor coverings only burn during a short period and hence one should also investigate the parameter C_b . We can note that for 25

kW/m^2 three materials have an exponent greater than 1. This will mean that after extinction of the material in the room the pyrolysis front will decrease as can be seen in figure 4 for three selected materials. In this figure we also observe a slow acceleration for the materials causing flashover. In the full scale test the flame spread was considerably faster and of the order of 0.1 m/s (table 2).

Considering the 35 kW/m^2 flux level, C_i is more severe although C_b shows more materials with an increasing flame spread after burnout of the initial surface. Also the flame spread acceleration corresponds better with the full scale results (figure 5, table 2 and reference [2]). Taking into account that the model starts with certain assumptions and that it is mainly limited to one specific scenario we can conclude that one can already determine which floor coverings might represent a risk in a wind-aided scenario.

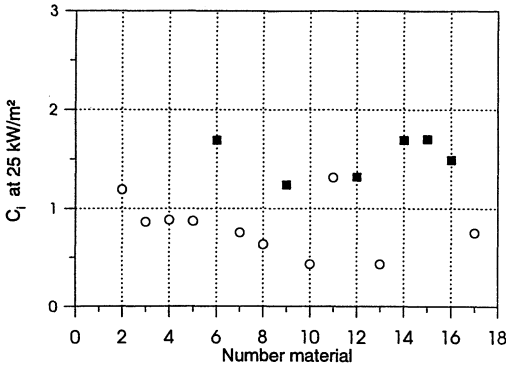


FIGURE 3: Graphical overview of parameter C_i at 25 kW/m^2 in the cone calorimeter.

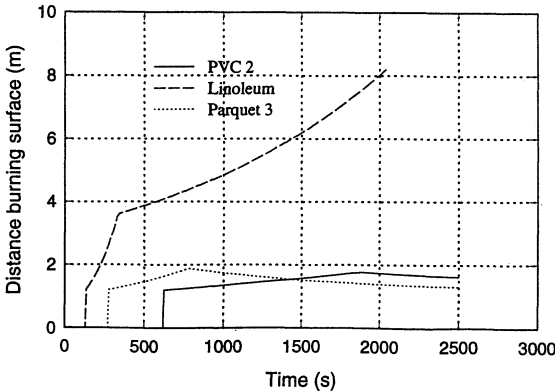


FIGURE 4: Calculated flame spread as a function of time for three materials by means of parameters determined at 25 kW/m^2 in the cone calorimeter.

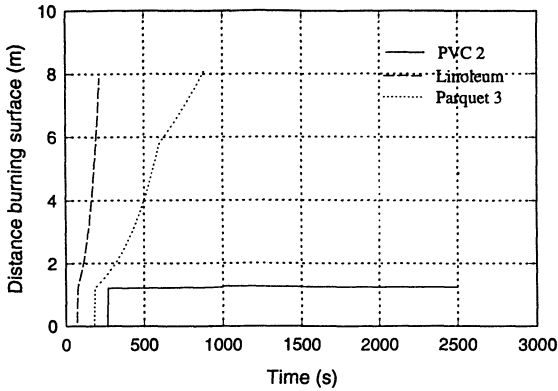


FIGURE 5: Calculated flame spread as a function of time for three materials using the parameters at 35 kW/m^2 in the cone calorimeter.

NUMERICAL MODEL FOR WIND-AIDED FLAME SPREAD OF FLOOR COVERINGS

Description

This model allows the user to perform predictions for the wind-aided flame spread of floor coverings using a flexible numerical approach. In this model the material is subdivided into n numerical strips with a width of Δx . Each strip i receives a total heat flux $\dot{q}_{t,i}''$. If we assume that the heat conduction between the strips is zero we can solve this problem one dimensionally. A schematical view of the geometric basis of this model is given in figure 6.

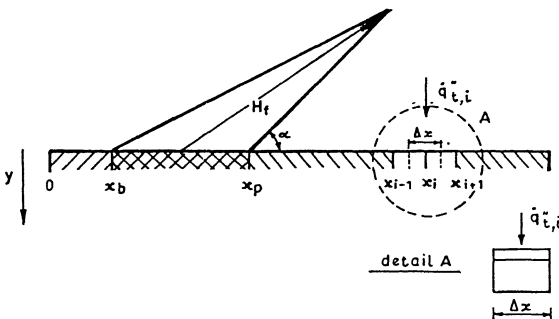


FIGURE 6. Schematical view of the numerical flame spread model.

The total heat flux, $\dot{q}_{t,i}''$, is calculated as follows:

$$\dot{q}_{t,i}'' = \dot{q}_{f,i}'' + \dot{q}_{e,i}'' + \dot{q}_{c,i}'' + \dot{q}_{co,i}'' + \dot{q}_{r,i}'' \quad (9)$$

Thus, the heat transfer equation for each strip is[8]:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c} \frac{\partial^2 T}{\partial y^2} \quad (10)$$

using the following initial and boundary conditions :

$$t = 0 \rightarrow T = T_{\infty} \quad y = 0 \rightarrow k \frac{\partial T}{\partial y} + \dot{q}_{t,i}'' = 0 \quad (11)$$

The heat transfer by radiation of the flames, $\dot{q}_{f,i}''$, can be calculated as follows [9]:

$$\dot{q}_{f,i}'' = \epsilon_f \sigma F_{v-i} (T_f^4 - T_{s,i}^4) \quad (12)$$

A constant value or a value depending on the smoke production of the material [10] is assumed for the emissivity of the flame, ϵ_f . A constant value of 1300 K [11] is assumed for the flame temperature, T_f . The viewfactor F_{v-i} can be determined by Figure 6 and reference [12].

The flame is represented as a triangle, the base of which is equal to the burning distance given by $(x_p - x_b)$. This triangle is bent depending on the orientation of the flow. In the first simulations an angle of 45° was taken based on visual observations made during the full scale tests. However in the future this angle can be calculated by means of the information from zone or field models in the specific configuration one wishes to investigate. The height of the triangle, H_f , depends on the height of the flame, which is linked to the heat release produced by the burning area. For practical reasons an exponential representation of the heat release curve was used, similar to previous work performed in the field of wall linings [7].

The relationship between the heat release and the height of the flame is given by the following empirical formula (reference [13]):

$$\frac{H_f}{D} = 3.7 Q^{*2/3} - 1.02 \quad (13)$$

The external heat flux, $\dot{q}_{e,i}''$, is taken as the downward radiation of the smoke gas layer below the ceiling produced by the thermal attack in the room. In this model heat fluxes, measured in the reference tests have been used. For a wind-aided flame spread the convective heat transfer, $\dot{q}_{c,i}''$, will be the heat transfer from the hot gases produced by the flames and flowing over the surface of the floor covering given as follows [14]:

$$\dot{q}_{c,i}'' = h (T_{f,i} - T_{s,i}) \quad (14)$$

The convection coefficient, h , can be calculated by applying traditional convective heat transfer theories [14]. The conduction in the gas phase, $\dot{q}_{co,i}''$, is only important near the pyrolysis front and can be calculated using references [2] and [14]. Conductive heat transfer in the gas phase is especially important in wind opposed flame spread [15]. For wind-aided

flame spread this factor can be neglected relative to the radiation from the flame as can be shown in a simplified heat transfer calculation [2].

Radiation heat losses at the surface, $\dot{q}_{r,i}''$, are given by :

$$\dot{q}_{r,i}'' = - \varepsilon_s \sigma (T_{s,i}^4 - T_\infty^4) \quad (15)$$

where the emissivity of the surface, ε_s , depends on the type of material. For this model a mean value of 0.9 has been taken [14]. Radiation losses are only important at higher temperatures, i.e., when the material reaches its ignition temperature.

The pyrolysis front is calculated by calculating the surface temperature of the material and comparing it with the corresponding surface ignition temperature for the material T_{ig} . This means that for each strip i the surface temperature is calculated by means of the numerical solution of the Duhamel integral [16]:

$$T_{s,i}(t) = T_\infty + \int_0^t (\dot{q}_{t,i}''(\tau)) \cdot \sqrt{\frac{t - \tau}{\pi k \rho c}} d\tau \quad (16)$$

Two values are necessary for the solution of this integral, namely the apparent $k\rho c$ and the ignition temperature T_{ig} . Both values are calculated by means of a set of ignition results in the cone calorimeter at different heat flux levels and by applying the theory developed by Janssens [17]. Since the floor coverings were tested in the cone calorimeter with a grid and using a slightly different substrate, a numerical heat transfer model based on a Cranck Nicholson algorithm was also developed to correct the ignition time for both deviations [2].

Results and discussion

Table 2 gives an overview of the simulation results including a comparison with the burned length in the full scale test results. In the full scale tests three different thermal attacks were used: first 100 kW period was applied for 10 minutes, then 300 kW for a further 10 minutes, followed by a period of 550 kW until flashover or for a maximum of 40 minutes. A detailed description of the full scale test set-up is given elsewhere [2][3]. Since the total floor covered distance in both room and corridor was 8710 mm the calculation was stopped when the pyrolysis front reached this distance. In those cases the extinction time corresponded to the time for the front to reach 8710 mm. As can be seen in table 2 the prediction of burned length is reasonably good in most cases. Those cases where the prediction is inadequate can be explained in terms of the assumptions or simplifications made for the model:

- For some materials the exponential representation of the heat release curve in the cone calorimeter is not correct (PVC 2 and carpet 3, see figure 7). Since the peak heat release in the cone calorimeter occurs closer to the end of the test, the predictions are more severe.
- Feedback of the radiation of the smoke gases produced by the material is not incorporated in the model. This explains slower predicted flame spread for materials with a high peak heat release (Parquet 3).

Considering that about 50 % of the materials are flame retarded, either by flame retarding treatment (FR cork, Carpet 2 and Rubber) or by the chemical nature of the material (PVC 1-5), one can conclude that the model is quite successful in predicting the risk of wind-aided flame spread of floor coverings.

TABLE 2: Results numerical simulation model				
Material	Ignition first strip in the room (s)	Extinction time (s)	Burned Distance (mm)	Burned distance FS tests (mm)
PVC 1	1542	2007	1110	<1200
PVC 2	1900	> 3000	6910	<1200
PVC 3	1660	2053	2410	6300
PVC 4	1480	1973	3410	3700
PVC 5	1360	1869	3910	2200
Linoleum	1662	2178	8710	8710
Parquet 1	1660	> 3000	6910	4700
Parquet 1	1540	> 3000	5910	3700
Parquet 3	2440	> 3000	3510	8710
Cork FR	2920	2990	3100	2900
Carpet 1	1900	2110	1000	1700
Carpet 2	1302	1492	8710	8710
Carpet 3	1242	1528	8310	1700
Carpet 4	1662	2066	8710	8710
Carpet 5	1962	2533	8710	8710
Carpet 6	1422	1770	8710	8710
Rubber	1720	> 3000	2110	1700

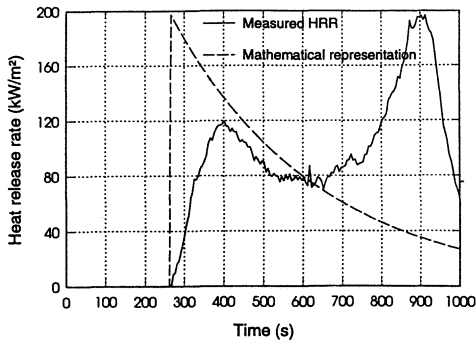


FIGURE 7: Comparison of exponential representation of the heat release curve and the real heat release curve for Carpet 3.

CONCLUSIONS

Two mathematical flame spread models for the prediction of wind-aided flame spread of floor coverings are presented based on the approach used for wall and ceiling linings. This approach is applied for the first time to floor coverings by taking into account specific assumptions related to horizontal wind-aided flame spread. An analytical model can be used for a fast and easy way to evaluate the risk of a given floor covering. A drawback of this solution is its limitation to a specific scenario. A numerical model has been developed for use when the flame spread needs to be calculated for varying conditions. If necessary, this model can be integrated in the future into a zone or field model to predict the fire development of a floor lining. These types of submodels are still lacking in zone and field models. Both models use only material characteristics determined in the cone calorimeter and show acceptable levels of accuracy comparable with those found in models used for the prediction of upward flame spread of wall linings.

The following improvements are suggested as future work :

- the use of the exact heat release curve, and
- the inclusion of the feedback of the radiation by the smoke gases produced by the material itself by using integration of the model in field and zone models.

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NOMENCLATURE

Δ_c	= distance where conductive heat transfer is occurring (m)
ϵ_f	= emissivity of the flame
ϵ_s	= emissivity of the surface
σ	= constant of Boltzmann ($5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$)
D	= equivalent diameter of the flame (m)
\dot{E}''	= heat release of the material (kW/m^2)
F_{v-i}	= view factor between flame and strip i
H_f	= flame height (m)
h	= convection coefficient ($\text{W/m}^2\text{K}$)
k_f	= factor which reflects the relationship flame length - heat release (m^2/kW)
k_g	= heat transfer coefficient of the smoke gases (W/mK)

Q^*	= a non dimensional factor for the heat release
$\dot{q}_{c,i}''$	= heat transfer by convection at the surface of strip i (W/m ²)
$\dot{q}_{co,i}''$	= heat transfer by conduction through the gas phase towards strip i (W/m ²)
$\dot{q}_{e,i}''$	= external heat flux from thermal attack, e.g. radiation of hot smoke gas layer under the ceiling (W/m ²)
$\dot{q}_{f,i}''$	= incident radiative heat flux from the flame (W/m ²)
$\dot{q}_{r,i}''$	= heat losses at the surface of strip i (negative term) (W/m ²)
$\dot{q}_{t,i}''$	= total incident heat flux on strip i (W/m ²)
T_f	= the flame temperature (K)
T_{fj}	= temperature of the smoke gases from the flame (K)
$T_{s,i}$	= surface temperature of strip i (K)
T_∞	= ambient temperature (K)
x_f	= flame length (m)
x_p	= pyrolysis distance (m)

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