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View factor in cone calorimeter testing

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ABSTRACT

This work focuses on algebraic derivations of geometric view factors (i) from plane element to interior of truncated cone in parallel configuration; (ii) from plane element to segment of interior of truncated cone in perpendicular configuration, to clarify irradiance-related uncertainties generated in cone calorimeter tests on intumescent-type fire resistant systems. Since such specimens undergo moving boundaries and perimeter surface exposures in the course of the bench-scaled fire tests, it is inevitable to encounter (i) irradiance intensifications on their top boundaries and (ii) irradiance influxes on their perimeter areas, which have not been reflected in conventional approaches. These irradiance-related issues can be solved by calculating diffuse view factors. Their derivations are achieved by using the contour integration method and verified by existing literature and direct measurements. The calculations are presented by graphical representations obtained through a process of mapping. This theoretical approach enables one to clarify the exact quantity of irradiance at any position under the heater, and thus to quantitatively analyse the resultant impacts of (i) non-uniform irradiance dispersions and (ii) non-consistent thermal loads occurring during the tests, on the quantification of radiation absorption. The findings demonstrate that discrepancies between exact calculations and conventional approximations, induced by these effects, are appreciable and hence should not be neglected in such quantifications. The derived formulae can be applied in solving radiation issues arising with analogous geometries, and the particulars in terms of irradiance can also promote the subsequent assessment of thermal behaviours of any specimen experiencing geometrical changes during cone calorimeter tests.

1. Introduction

A bench-scaled cone calorimeter, standardised in BS 476-15 [1], has been widely used to test flammability of various condensed materials in the field of fire safety engineering. This apparatus facilitates regulating a radiant heat flux and is capable of imposing a consistent thermal load on given specimens during tests, which are important aspects when creating a stable fire test environment. The steady heating condition has extended its application, beyond the conventional purpose, to evaluating thermal behaviours and performances of intumescent-type fire retardant systems since the early 2000s [2–10]. With this extended application, doubts have recently arisen about whether thermal boundaries of the polymeric samples tested with this instrument are either adequately clarified or understood. This is because this type of material exhibits anisotropic volume progressions, induced by thermochemical decompositions, by up to several tens of times its dry film thickness when subjected to a heat. In cone calorimeter tests on such materials, the thermal reaction leads to, primarily having their top boundaries moved toward the spatially stationary conical heater, and secondarily having their perimeter surfaces progressively extended in the *z*-direction and newly exposed to the heating element, as described in Fig. 1.

The quantity of incident radiant flux on given specimens is highly critical in solving heat-related issues of flammability, thermal behaviours and performances [11]. In this bench-scaled fire test, irradiance is typically estimated by physical measurements using a heat flux probe (e.g., Schmidt-Boelter gauge) placed along the cone axis through the central point of test samples in a calibration stage [12]. Up until now, a single value measured in this initial stage has been interpreted as a constant thermal load in the entire course of tests, even on intumescent-type materials. However, this conventional approach does not reflect

- The intensification of irradiance on the top surface of specimens, developed as the boundaries progressively approach the heat source. The alteration of thermal loads in the process of testing can lead to an underestimate of the amount of heat absorption, by up to approximately 1.5 times less than the actual value.

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Nomenclature

A	surface area
b,q,s,t	spacing parameters
C	contour
F	view factor
h,h_2	vertical spacing parameter from cone baseplate to top surface of specimen
h_4	vertical spacing parameter from cone upperplate to top surface of specimen
H	height of conical heater
k	coverage factor
ℓ, m, n	direction cosines
$\vec{n}$	normal vector
p	horizontal spacing parameter from the origin of the coordinate system
P	general point upon contours
$\dot{q}''$	radiant heat flux (W/m^2)
r	radial dimension
u	standard uncertainty
u_c	combined uncertainty
U	expanded uncertainty
x, y, z	Cartesian coordinates

Greek symbols

α	absorptivity
$\beta, \theta, \varphi, \phi$	angular integration variables
ρ	spacing parameter
σ	Stefan–Boltzmann constant (W/m^2 K^4)
ω	solid angle

Subscripts

a	arc
abs	absorbed
$emit$	emitted
g	heat flux gauge
$heater$	conical heater
ℓ	line
s	specimen

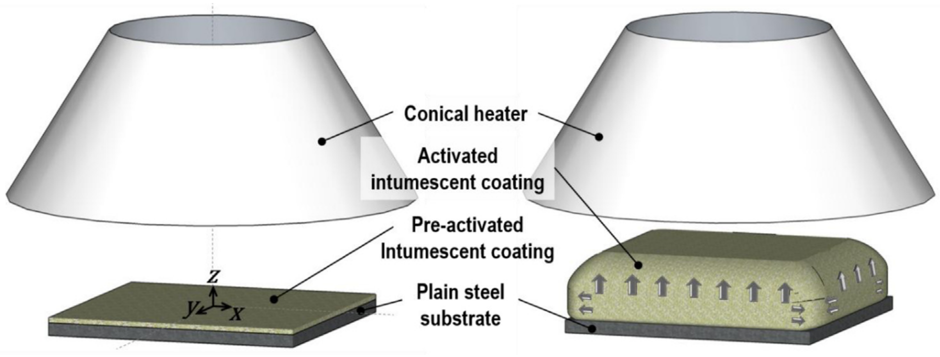
- The influx of the radiant heat arriving at the extended perimeter areas of specimens. With expansion factors (i.e., the difference between fully expanded coating thickness and pre-activated coating thickness, divided by pre-activated coating thickness) in a general range of 5–62, identified in previous studies [3,10], the surface area of fully extended perimeter surfaces easily exceeds that of the top surface on which heat is mainly absorbed, which is normally 0.01 m^2 in dimension. Under the changed exposure conditions, the quantity of the heat absorbed by the perimeter areas can comprise a noticeable portion of the total heat absorption.

These two aspects, in terms of non-consistent thermal loading, cannot be neglected in any investigation utilising the cone calorimetry into material samples undergoing moving boundaries and appreciable side exposures.

Difficulties in theoretically solving the issues of (i) the variation in thermal load on top surfaces and (ii) the inclusion of the neglected irradiance on side surfaces originate from the unique spatial configuration between the truncated cone shaped emitter and a rectangular recipient. From the viewpoint of radiation transfer, this arrangement provokes that both the distance between each infinitesimal area of the two domains and the angles between the distance lengthwise line and each elemental area's normal vector vary all over the exposed surfaces of the recipient. The built-in geometrical characteristics of this apparatus, therefore, result in non-uniform dispersions of irradiance all over the exposed surfaces. In relation to this nonlinear thermal loading, recent research has established that the irradiance on the top surface is not uniformly distributed outside the 50 mm^2 central area, by physically measuring irradiances or numerically calculating geometric view factors [13–16]. However, theoretical derivations from the principles of thermal radiation have not been adequately demonstrated to resolve the thermal issues in relation to the moving boundaries and side exposures.

This work aims to clarify the exact quantities of irradiances produced in bench-scale cone calorimeter tests so as to improve the subsequent assessment process of intumescent-type samples tested with the instrument. This objective is achieved by

- Algebraically deriving view factors using contour integration to find relations for factors (i) from plane element to interior of truncated cone in parallel configuration; (ii) from plane element to segment of interior of truncated cone in perpendicular configuration.
- Verifying the numerical calculations by direct measurements and pertinent existing data sets [13,14].



(a) Initial stage (b) Intumescent stage

Fig. 1. Schematics of geometrical changes of intumescent systems occurring during cone calorimeter tests.