Fire Safety Journal xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Two-layer zone model including entrainment into the horizontally spreading smoke under the ceiling for application to fires in large area rooms

Tomoaki Nishino

Building Research Institute, Japan, Tachihara 1, Tsukuba, Ibaraki 305-0802, Japan

ARTICLE INFO

Keywords:
Modeling
Smoke
Entrainment
Ceiling jet
Zone model
Large space

ABSTRACT

A model for smoke filling in a large room was developed that considers entrainment into the horizontally spreading smoke under the ceiling. This was accomplished by incorporating a simple model for the spreading ceiling jet into the two-layer zone model. Here, the proposed model was validated by focusing on the horizontal smoke spread phase on the basis of the previous experimental data of smoke spread in a large office room. The calculated results were in good agreement with the experimental data. In addition, a case study on the smoke filling in a large room was conducted to clarify the characteristics of the proposed model. As a result, the proposed model can predict the underside of the smoke layer to be lower than the two-layer zone model.

1. Introduction

The two-layer zone model (e.g. BRI2002 [1]) has been frequently used in fire evacuation safety design in Japan because the smoke transport can be predicted in a time series, and the effort required for the computation is much smaller compared with a computational fluid dynamics simulation. This model assumes that smoke layer is formed instantaneously, and the mass flow rate into the layer depends on the entrainment in the plume region. In a space having a high ceiling compared with its width, the entrainment in the plume region dominates the mass flow rate. However, in a space having a large width compared with its ceiling height, the entrainment through the underside of the spreading ceiling jet increases the mass of the smoke until the ceiling jet reaches the side walls. Therefore, there is a possibility that the two-layer zone model, which neglects such an influence, will predict the underside of the smoke layer to be higher in a large space.

A number of studies have been conducted experimentally and theoretically to clarify the characteristics of the ceiling jet [2–6], such as temperature, velocity and thickness, as the ceiling jet behavior is important for predicting the actuation of smoke detectors and sprinklers. In recent years, Suzuki [7] has extended the theoretical steady-state ceiling jet model by Alpert [2] to an unsteady model, given the limitations of the applicability of the two-layer zone model to a large space. In the model by Suzuki [7], the governing equations of the spreading ceiling jet are solved by dividing the area into multiple sections in the radial direction. However, given that the descent of smoke layer is predicted by the two-layer zone model after the spreading ceiling jet reaches the side walls, another approach is to simplify the spreading ceiling jet based on a concept similar to the zone model. Oka et al. [8] have estimated the empirical formula for the mass flow rate in the spreading ceiling jet on the basis of the measurement of carbon dioxide concentration. This formula, which is applicable to a radial distance about 10 times larger than a ceiling height, makes it possible to predict the mass flow rate considering not only the entrainment in the plume region but also the entrainment through the underside of the spreading ceiling jet.

The aim of this work is to develop a computational model to predict the smoke filling in a large room considering the entrainment into the horizontally spreading smoke under the ceiling. Here, a simple model for the spreading ceiling jet was incorporated into the two-layer zone model. As the focus of the model is on the smoke filling in a single room, the formulation of mass transfer through openings and mechanical ventilation was omitted, but the model can be easily extended. In addition, the reverse current [9] that the ceiling jet returns in the direction of the fire source after reaching the side walls was not considered as the first step of model development. Here, the proposed model was validated by focusing on the horizontal smoke spread phase on the basis of the previous experimental data of smoke spread in a large room [7,10]. In addition, a case study on the smoke filling in a large room was conducted to clarify the characteristics of the proposed model.

E-mail address: nishino@kenken.go.jp.

http://dx.doi.org/10.1016/j.firesaf.2017.03.049
Received 13 February 2017; Received in revised form 22 March 2017; Accepted 25 March 2017
0379-7112/

Nomenclature

Alphabets

A_f	floor area (m^2)
A_s	smoke projected area (m^2)
A_w	wall area contacting with smoke layer (m^2)
C_f	friction coefficient (–)
c_p	specific heat (kJ/kg K)
D	diameter of fire source (m)
g	gravity acceleration (m/s^2)
H_c	ceiling height (m)
h_k	heat transfer coefficient (kW/m^2 K)
$\dot{m}_e$	mass entrainment rate through the underside of spreading ceiling jet (kg/s)
$\dot{m}_p$	mass flow rate in fire plume (kg/s)
$\dot{Q}_f$	heat release rate of fire source (kW)
$\dot{Q}_{f,conv}$	convective part of heat release rate of fire source (kW)
$\dot{Q}_{lc}$	heat loss rate to ceiling surface (kW)
$\dot{Q}_{lw}$	heat loss rate to wall surface (kW)
R_e	Reynolds number (–)
r_s	smoke travel distance (m)
T_s	smoke temperature (K)
T_∞	air temperature (K)
t	time (s)
U_s	smoke velocity (m/s)
Z_s	smoke thickness (m)
Z_0	location of virtual point source (m)

Greeks

α	fire growth rate (kW/s^2)
ν	dynamic viscosity (m^2/s)
ρ_s	smoke density (kg/m^3)
ρ_∞	air density (kg/m^3)

Suffix

c	ceiling
s	smoke
w	wall
∞	ambient
0	initial condition

2. Fire smoke filling model in a large room

Fig. 1 is a schematic of a fire smoke filling model in a large room. In this model, assuming that a fire source of known heat release rate occurs in a space where there are no vents above the smoke layer, physical quantities of smoke, such as temperature and thickness, are predicted in a time series by dividing the smoke filling into the following two phases:

I. Horizontal smoke spread until the spreading ceiling jet reaches the side walls
II. Smoke layer descent after the spreading ceiling jet reaches the side walls.

Here, assuming that the smoke spreads in axial symmetry under the ceiling until reaching the side walls and the front reaches the walls at the same time regardless of location, each phase is defined as follows by using the travel distance of the smoke r_s:

I. The projected area of the smoke is less than the room area $\pi r_s^2 < A_f$
II. The projected area of the smoke is equal to the room area $\pi r_s^2 = A_f$.

The assumption that there are no vents above the smoke layer, a treatment only in this paper, is intended to focus on the formulation of the horizontal smoke spread, because pressure and mass transfer between spaces need not be evaluated.

2.1. Assumptions

2.1.1. Horizontal smoke spread

The following assumptions are made for modeling of the horizontal smoke spread:

(I-a) Fire plume turns to the horizontal direction after hitting the ceiling, and forms the spreading ceiling jet in axial symmetry.

(I-b) The spreading ceiling jet has a cylindrical body with a uniform thickness neglecting the distribution in the radial direction, and is sharply distinguished from ambient air.

(I-c) The temperature of the spreading ceiling jet is uniform regardless of location neglecting the distribution in the radial and vertical direction.

(I-d) The spreading ceiling jet is a uniform flow parallel to the radial direction at a given point in time neglecting the distribution of velocity in the radial and vertical direction.

(I-e) Mass transfer across the boundary of the spreading ceiling jet occurs by the fire plume and by entrainment through the underside of the spreading ceiling jet.

(I-f) Heat transfer across the boundary of the spreading ceiling jet occurs by radiative and convective heat transfer between the spreading ceiling jet and the ceiling surface, as well as that associated with the mass transfer referred in (I-e).

(I-g) Momentum transfer across the boundary of the spreading ceiling jet occurs only in the radial direction by pressure due to density difference between the spreading ceiling jet and the ambient

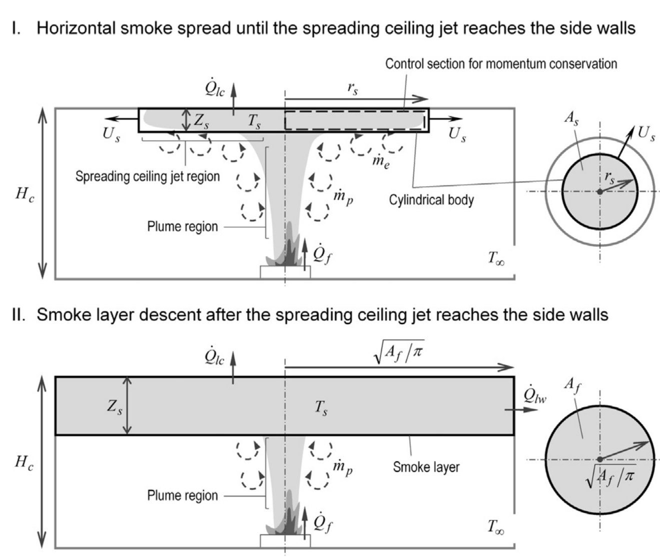

Fig. 1. Schematic of a fire smoke filling model in a large room.