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A small-world network model for the simulation of fire spread onboard naval vessels

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ABSTRACT

This work is devoted to the development of a small-world network model to predict real-time fire spread onboard naval vessels. This model takes into account short-range and long-range connections between neighboring and remote network compartments. Fire ignition and flashover, as well as fire transmissions through the walls and ventilation ducts are simulated using time-dependent normal probability density functions. Mean durations of fire transmission through the walls and ducts are determined by a three-zone model and a one-dimensional CFD code, respectively. Specific experiments are conducted in a steel room, representative of a naval vessel compartment, in order to validate the zone model. Then a proof of concept is developed by applying the network model to a full-scale vessel mockup composed of 113 compartments on 7 decks. A statistical study is conducted to produce fire risk maps, classifying the vessel compartments according to their propensity to burn.

1. Introduction

Fire risk assessment in multi-compartment enclosures is a major issue with consequences for lives, properties, structures, activities and environment. These consequences become even more critical when dealing with naval vessels. In such a context, fire spread can result in a loss of mission capability. Furthermore, the protection and evacuation of people in fire situation is an absolute priority. Hence, it is crucial to rapidly detect fires and deal with them. Research and development on fire spread models in multi-compartment enclosures underwent several evolutions in the past decades. Until the early 2000s, such models were often developed using a purely probabilistic approach because of the difficulty to take into account all the physical factors affecting the growth and spread of fire. In [1], Ramachandran outlined and analyzed the significant studies until the year 2002 that are based on the following approaches: epidemic model [2,3], random-walk theory [4,5], Markov processes [6–8], percolation processes [9,10] and probabilistic networks [11,12]. As mentioned by Ramachandran in his study [1], these models do not allow to correctly model the propagation of the fire in a multi-compartment enclosure because of many reasons, mainly their incapacity to take into account the dynamics of the propagation process or the physics of the interaction between compartments within small and long distances. Therefore, deterministic ([13–18]), probabilistic ([19–24]) and Bayesian [25,26] network models including all or part of the physical aspects related to the fire spread in multi-compartment enclosures were developed. The present study is based on a variant of the so-called small-world network model [27], which considers probabilistic local contacts between neighboring compartments and long-range contacts between distant compartments via ventilation ducts. It takes into account the dynamic nature of fire spread and the physics of fire and transmissions between compartments, as inspired by the work of Cheng and Hadjisophocleous [26]. Moreover, this network is polydisperse (i.e. compartments may differ in size) and amorphous (i.e. no geometrical regularity) which allows to study realistic layouts of complex-shaped compartments. The dynamic nature of the model is based on time-dependent probabilities of fire growth and fire transmission through the walls and ventilation ducts. Mean durations of fire transmission through the walls are determined by a three-zone model developed by the Direction Générale de l'Armement (DGA), taking into account the effect of fire load, compartment geometry, wall insulation and openings, whereas a one-dimensional CFD model has been developed for simulating the flow and heat transfer in ventilation ducts. The paper is organized as follows. First, we present the network model and the assumptions upon which it is based. Second, we provide the procedure used to determine model parameters. Then a proof of concept is

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Nomenclature

A_0	opening area (m^2)
A_F	compartment floor area (m^2)
C	compartment
c_p	isobaric specific heat (J/kg/K)
H_0	opening height (m)
m	fuel mass (kg)
$\dot{m}$	mass loss rate (kg/s)
p_{fd}	probability density function of fully developed fire
$p_{t,i}$	probability density function of fire transmission ($i = h, vu, vd, d$)
P_{fd}	cumulative probability of fully developed fire
$P_{t,i}$	cumulative probability of fire transmission ($i = h, vu, vd, d$)
$P_{ig,i}$	probability of fire ignition ($i = h, vu, vd, d$)
P_{spread}	probability of fire spread
R	gas constant (J/mol/K)
r	radius (m)
T	temperature (K)
t	time (s)
w_f	fuel load (kg/m^2)

Greek

ΔH_c	heat of combustion (J/kg)
λ	thermal conductivity (W/m/K)
μ	mean value of the pdf (s)
φ	specific fuel area (m^2/kg)
ρ	density (kg/m^3)
σ	standard deviation of the pdf (s)

Subscripts

d	ventilation duct
de	fire decay phase
eq	equivalent
fd	fully-developed fire phase
fo	flashover
h	horizontal
vd	vertical downward
vu	vertical upward
lim	limit
nonref	non-reference compartment
p	wall
ref	reference compartment
t	transmission

Superscripts

~	theoretical

developed by applying the network model to a full-scale vessel mockup. In the last section, the model is used to establish a fire risk map of the mockup, ranking compartments by their propensity to burn.

2. Mathematical model

2.1. Network model

From the compartment connectivity information, it is possible to define a graph representation of the possible pathways (wall, duct, opening) for fire to spread from the fire compartment to the others vessel compartments: through a wall or an opening connecting two adjacent compartments, through a ventilation duct connecting two adjacent or remote compartments (Fig. 1). In such a graph, the nodes represent the compartments and the links represent the connections between two compartments.

There are six main types of compartments that are likely to spread fire onboard naval vessels. They are summarized in Table 1.

If a fire occurs in a compartment, the compartment fire may undergo the phases of growth, fully-developed and decay. Flashover is the rapid transition from a growing to fully-developed fire in which all combustible items are involved in fire. As usually done for naval ship applications, the time evolution of the gas temperature inside a fire compartment is assumed to follow the empirical temperature law given by [28].

$$T_g = 20 + 160(t \times \alpha)^{0.4} \tag{1}$$

where t is in minutes and α is a fire growth parameter, which depends both on the type of compartment and vessel context. The values of α given in Table 2 correspond to a vessel context where all doors are closed and ventilation is stopped after 10 min of fire.

The model is based on the following assumptions:

A1: Following Cheng and Hadjisophocleous [26], the occurrence of flashover in a compartment, the transmission of fire through walls and ventilation ducts, and fire spread from one compartment to another compartment are represented by time-dependent Gaussian probability density functions, with an associated standard deviation of 15% of the mean value.

A2: The probability of transmission through an opening is equal to 1.

A3: The ignition of a target compartment 2 (C2) by a fire compartment 1 (C1) occurs only if the fire in C1 is fully developed and if the transmission from C1 to C2 already happened.

A4: Fire transmission through the wall occurs when the temperature of the outer face of the wall exceeds the initial temperature by 140 degrees, as recommended by the SOLAS convention [29].

A5: The transmission probability in the decay phase is zero. A preliminary study has shown that the decay phase had no effect on

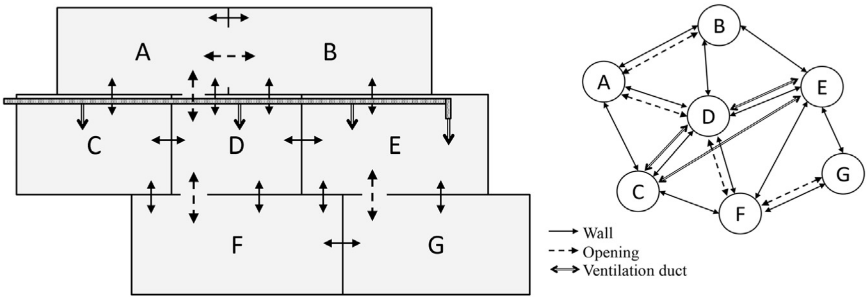

Fig. 1. Network connectivity.

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