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Numerical analysis on plume temperature properties formed above a harmonically oscillating fire source

Hideyuki Oka[a,*], Yasushi Oka[b]

[a] Maritime Risk Assessment Department, National Maritime Research Institute, National Institute of Maritime, Port and Aviation Technology, 6-38-1, Shinkawa, Mitaka, Tokyo 181-0004, Japan
[b] Faculty of Environment and Information Sciences, Yokohama National University, 79-7, Tokiwadai, Hodogaya-ku, Yokohama, Kanagawa 240-8501, Japan

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ABSTRACT

Large eddy simulation (LES) of turbulent buoyant plumes formed above an oscillating fire source has been carried out so as to clarify their temperature properties in the offshore environment. For the sake of simplicity, we are concerned here only with a rolling environment among six-degree-of-freedom system of complex ship motion. Furthermore, under the assumption of a small rolling angle, unsteady fire source movement associated with the rolling motion can be approximated by simple harmonic oscillation in the horizontal direction. Numerical results obtained under several sets of oscillation conditions, especially under different amplitude conditions, are compared with temperature variations of conventional axisymmetric and two-dimensional fire plumes above stationary sources. Consequently, it has been clarified that in the case where the amplitude is four times longer than the side length of a square source, the present buoyant plumes exhibit almost the same feature as the two-dimensional fire plume in the lower part of the buoyant plume region. On the other hand, it has been found that for any value of amplitude, the temperature properties are close to those of axisymmetric plumes in the upper part of the buoyant plume region. Based on these findings, a simple theoretical model to estimate the variation in mean excess temperature as a function of elevation has been developed by the use of a well-recognized, semi-analytical solution of the axisymmetric plume formed above a virtual point source. It has been confirmed that this simple model can reasonably reproduce the same plume features as obtained by the LES simulations.

1. Introduction

Ship fire is one of serious marine accidents, which has claimed numerous casualties in the history of accidents at sea. Thus, the fire safety measures in the offshore environment are critically important, but onboard safety regulations are determined on the basis of those used for shore-based architectural design. A number of studies on the flame behavior, fire-induced flows and smoke movement in a building compartment have already been conducted in the field of fire safety engineering. In these conventional studies fire source location is assumed to be temporally stable. On the other hand, in the offshore environment the fire source location varies with time due to oscillation associated with complex ship motions, so that the properties of buoyancy-driven flow formed above an oscillating fire source are expected to be substantially different from those in a compartment of shore-based facilities.

Fire plumes play a very important role in fire dynamics as the most fundamental phenomenon, since they serve as a driving force to transport heat and combustion products such as carbon oxide and soot. In spite of many previous studies on fire plume features [1,2], as far as the authors know, there is no research on the deterministic properties of turbulent buoyant plumes originating from an oscillating fire source. Accordingly, it is not clear whether fire plume correlations obtained in the onshore environment can be applicable to ship fire phenomena, since they are derived under the condition that the fire source is fixed at an initially given location.

Based on the above motivation, as a preliminary study numerical simulations on the fire plume formed above an oscillating source were carried out by using the Fire Dynamics Simulator version 5 (FDS5) in prior work [3]. FDS is one of the current state-of-the-art computer programs based on computational fluid dynamics (CFD) techniques for fire-related phenomena, developed by the National Institute of Standard and Technology, USA. In that study, a rolling environment is considered as a typical ship behavior out of six degrees of freedom of

* Corresponding author.
E-mail address: hoka@nmri.go.jp (H. Oka).

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motion. Theoretically, the ship rolling is treated as the motion of a simple pendulum, the rotation center of which is expedientially assumed to be the center of mass [4]. Furthermore, with a focus on the motion of small angular amplitude, the ship rolling motion can be simplified in such a way that it obeys a simple harmonic oscillation approximately. In fact, when the angular amplitude is not more than about 10 degrees, the variance of the gravitational force component in the radial direction of the single pendulum is less than about 1% throughout one period. Under this simplification, it has been found that fire plumes formed above an oscillating source exhibit widely recognized features of two-dimensional and axisymmetric plumes in lower and upper plume regions, respectively. In other words, the mean excess temperature scales as the elevation from the fire source to the −1 power and to the −5/3 power in the lower and upper plume regions, respectively.

In the prior work [3], however, qualitative properties of fire plumes formed above an oscillating source were investigated only under a certain specific set of conditions of simple harmonic oscillation. It is necessary to confirm the validity of the above-mentioned properties under different sets of oscillation conditions by varying the amplitude and period. To examine the effect of the oscillation period, CFD-based numerical simulations have been also carried out [5] in the same way as in the previous work [3]. Regardless of oscillation periods, the range of which are considered in the typical rolling environment, the feature of variations in mean excess temperature has been almost identical to that of conventional two-dimensional plumes formed above a line fire source in the lower part of the buoyant plume region, whereas in relatively short periods temperature decay properties depend upon the oscillation period in the upper buoyant plume region. The reason is that in these short-period cases the speeds of periodically varying crosswinds induced by the fire source oscillation are relatively higher than those in the case of longer periods.

In the present study, numerical simulations have been carried out so as to investigate the effect of the oscillation amplitude on the fire plume formed above the harmonically oscillating source. Furthermore, a simple theoretical model to estimate the variation in excess temperature has been proposed by the use of a classical, semi-analytical solution of a conventional axisymmetric plume formed above a virtual point source. The remainder of this paper is organized as follows. In Section 2, we briefly mention the laboratory-scale fire plume considered in the present study. Then, we outline the numerical simulation method as well as the way to simulate fire source oscillation in Section 3. In Section 4, numerical results are provided to examine the effect of the amplitude on plume temperature properties formed above the oscillating fire source. This is followed by the development of the simple theoretical model, which is the main focus of the present work. Finally, conclusions are stated in Section 5.

2. Laboratory-scale fire plume above an oscillating source

In a frame of reference moving with a ship, the gravitational force components periodically vary with time. In the same manner as the previous work [3,5], we assume that the motion of a fire source obeys a simple harmonic oscillation on a horizontal plane under the condition of a small rolling angle. The schematic view of a laboratory-scale fire plume originating from such an oscillating source is shown in Fig. 1. A square gas burner is used as a fire source in consideration of experiments under way. The burner is 0.42 m tall and the area of its horizontal section is 0.1×0.1 m. The oscillation period is set to 12 s by reference to similar studies [6,7] in other academic disciplines, in which the effects of ship rolling motion were investigated by laboratory-scale experiments. As to the oscillation amplitude, four different cases are examined by varying it from 0.1 to 0.4 m by an increment of 0.1 m. The fuel supplied to the gas burner is propane (C_3H_8), and heat release rates selected here are three cases of 5, 10 and 15 kW.

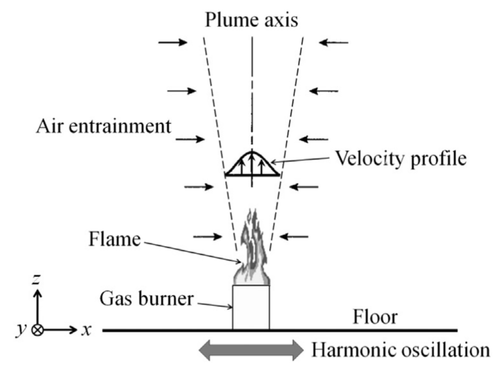

Fig. 1. Schematic illustration of a fire plume above an oscillating gas burner.

3. Numerical simulation method

3.1. Computational fluid dynamics model

The Fire Dynamics Simulator (FDS) [8,9] is the most widely used software application as a research and/or engineering tool in the community of fire safety engineering, and it is freely available as open-source software. A number of studies on verification and validation have been also conducted to evaluate it [10,11]. It has been confirmed that calculation times required by FDS6 is nearly twice as long as that by FDS5 in fire plume simulations on McCaffrey's experiments [12]. In this study, therefore, FDS5 (version 5.5.1) is used rather than FDS6 to reduce computational costs.

FDS solves the low-Mach number form of the compressible Navier-Stokes equations [13]. The governing equations are the continuity, momentum, mixture fraction, and velocity divergence equations and the ideal gas law, which are approximated using second-order accurate finite differences on a collection of three-dimensional rectilinear grids. Variables to be solved numerically are assigned in accordance with a staggered grid. These variables are advanced in time using an explicit second-order predictor/corrector scheme. The spatial discretization is based on a central difference scheme. The linear algebraic system arising from the discretization of a Poisson equation for pressure is solved by a fast, direct method that utilized fast Fourier transforms. For details on numerics in FDS, refer to McGrattan et al. [14].

For fire sources, a non-premixed turbulent combustion model is originally developed to estimate the heat release rate on the basis of the popular eddy dissipative concept (EDC) model [15]. Furthermore, this combustion model is modified for under-ventilated fire configurations in which flame extinction is a significant factor [16]. The radiative heat emitted from this fire source is obtained as a solution of radiative transfer equation for an absorbing-emitting and non-scattering grey medium, which is solved by techniques similar to those for convective transport in finite volume methods for fluid flow [17]. More details of the model implementation are also provided by McGrattan et al. [14].

In FDS, turbulence modeling strategy is based on large eddy simulation (LES). To approximate the turbulent stress τ, the Smagorinsky model with a constant coefficient [18] is employed as a sub-grid scale (SGS) model in FDS5. This SGS model is widely used in a variety of engineering fields owing to its simplicity and high numerical stability. The model constant C_s is set to the default value of 0.2 in this study, since it has been confirmed that numerical simulation results with this value nicely reproduce McCaffrey's experiments [12] in the buoyant plume region. As for the other turbulence model parameters, the SGS Prandtl number Pr_t and the SGS Schmidt number Sc_t are also set to the default value of 0.5 due to the fact that their effect on fire plumes is small [19,20].

In order to allow for the fire source oscillation, the governing equations are solved in a moving reference frame fixed to the gas burner. Hence, the inertial force attributable to periodic motion of the