A MODEL FOR PREDICTING FIRE SUPPRESSION IN SPACES PROTECTED BY WATER MIST SYSTEMS

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ABSTRACT

A model was developed to predict the effectiveness of water mist systems. The model assumes that fires are extinguished by oxygen displacement. This model is developed only for obstructed spray fires. The model is based on conservation of energy and requires the following input parameters: fire size, compartment geometry, vent area, and water flow rate. The temperatures and oxygen concentrations predicted by the model can be used to determine the smallest fire that will produce adequate water vapor to sufficiently dilute the oxygen concentration to below the LOI.

The model was validated using the results of the machinery space tests conducted for the U.S. Coast Guard. For the compartment geometry and vent size used during these tests (IMO Test Protocol), the model was able to accurately predict the steady-state compartment temperatures during the tests consisting of the smaller spray fires. The larger fires were extinguished before steady-state conditions were reached. This was also predicted by the model. The results of the model were used to accurately predict the smallest fire that will produce adequate water vapor to result in extinction.

Additional validation work is required to assess the limitations of the model.

INTRODUCTION

Water mist fire suppression systems are being seriously considered as replacements for Halon 1301 total flooding systems in machinery space applications. The US Army [1], the US Coast Guard [2], and the US Navy [3,4] have each conducted separate investigations into the use of water mist in this application. The US Navy investigation was conducted in a closed compartment. Both the US Army and US Coast Guard investigations were based on the International Maritime Organization (IMO) test protocol for evaluating alternative arrangements for halon fire extinguishing systems [5] and were conducted in well ventilated compartments (2 x 2 m [6.5 x 6.5 ft] vent opening). The tests conducted to date form a substantial database for water mist systems installed machinery spaces having volumes between 250-750 m^3 and varying degrees of ventilation.

During these full-scale machinery space fire tests, steady temperatures were observed shortly after mist system activation. These steady conditions were more predominant for the smaller obstructed fires than either the unobstructed fires or the larger fires in general. In all the tests where steady-state conditions occurred, the steady-state temperatures ranged from 50-70 "C. The lack of steady-state conditions for the unobstructed fires is believed to result from direct interaction of the mist spray and the fire. The steady thermal conditions are not always produced by the larger fires due to rapid fire extinguishment by oxygen depletion and dilution. The model developed here is designed to address the conditions for extinction of small obstructed fires, which are the most challenging fire scenarios.

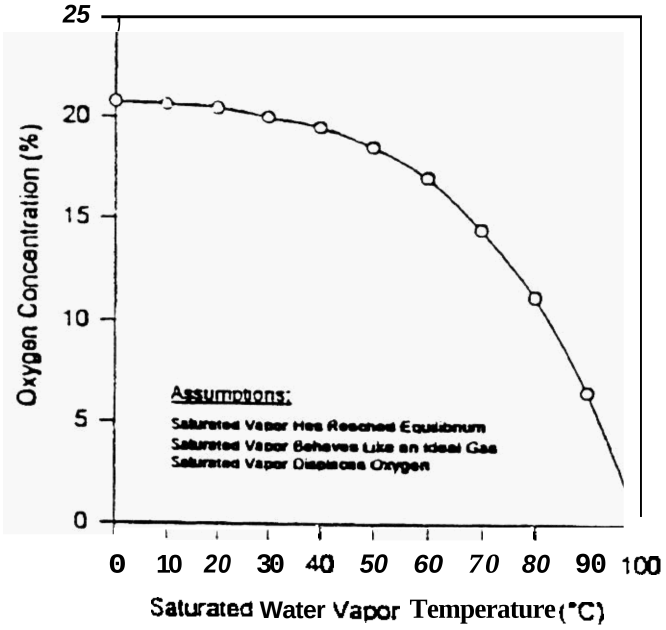

Fig. 1. Oxygen concentration **of** saturated air

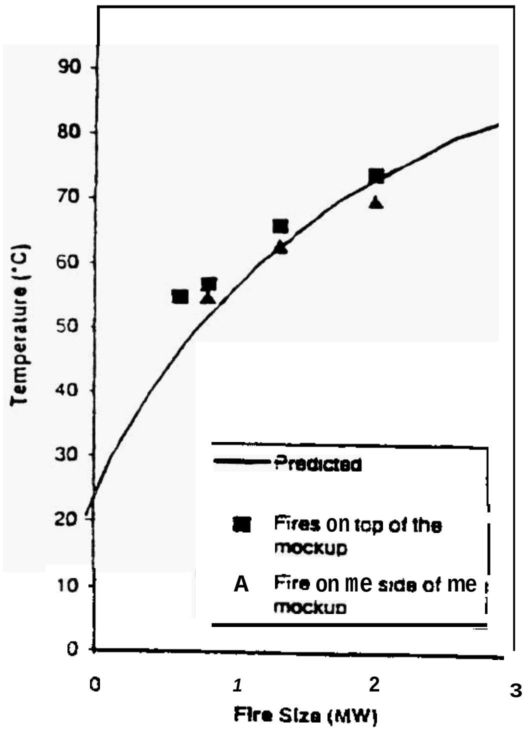

Fig. **2.** Predicted temperatures

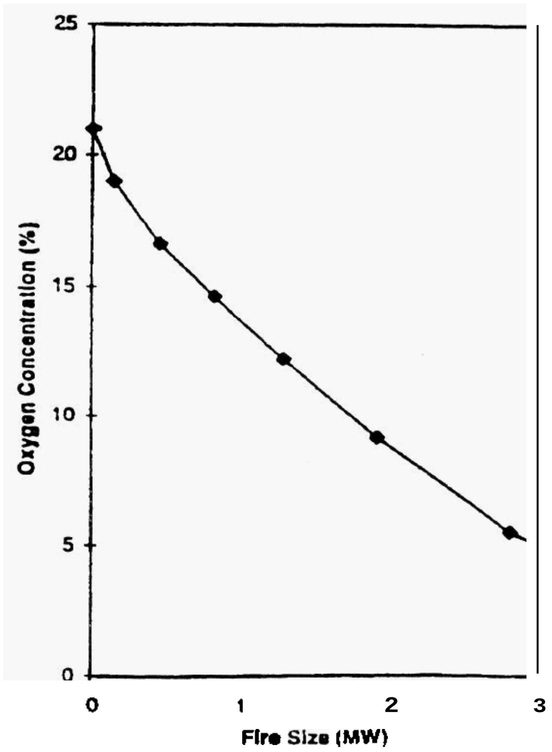

Fig. 3. Predicted oxygen concentrations

The significance of these temperatures became apparent when evaluating the oxygen concentration in the space during extinguishment. During this oxygen evaluation, it was determined that the dilution of oxygen by saturated vapor at these temperatures can significantly reduce the oxygen available for combustion. In fact, based on a few assumptions, it **was** determined that the water vapor in saturated air at temperatures above 80 °C is sufficient to dilute the oxygen concentration below the limiting oxygen index for most fuels (Figure 1). This information prompted the development of a model that could be used to predict the steady-state temperatures in the space.

EXPERIMENTAL SETUP

The US Coast Guard (USCG) investigation was conducted in a simulated machinery space on the test vessel, Mayo Lykes, located at Little Sand Island in Mobile, AL. The simulated machinery space was roughly 6.9 x 11.1 x 7.3 m (560 m^3) and is bounded by 1.25 cm steel bulkheads. **A** 2 x 2 m vent **was** located aft in the space on the second deck level. This vent remained opened during the tests. **A** diesel engine mockup was located in the center of the space.

Five water mist fire extinguishing systems were evaluated during this test series (Grinnell AquaMist, Kidde Fenwal, Reliable, Securiplex, and Spraying Systems). The candidate nozzles covered the range of available technologies from high- and low-pressure single-fluid systems to twin-fluid systems. The system operating pressures ranged from 5.5 to 70 bar (80-1000 psi). The flow rates **of** the individual nozzles ranged from 5.0 to 11.4 liters/min (1.3 **to *3.0*** gal/min). The candidate nozzles were evaluated with a 1.5-m (5.0 ft) nozzle spacing. The total system flow rates ranged from 140-340 liters/min (2.3-5.6 kg/sec).

The systems were evaluated against 18 fire scenarios, 13 IMO fire scenarios, and ***5*** IMO fire scenarios conducted with a lower flash point fuel (heptane rather than diesel). The model was validated using the heptane spray fires located on the side of the diesel engine mockup. These fires ranged in size from 0.6-6.0 MW and were well obstructed.

MODEL DEVELOPMENT AND VALIDATION

The model was developed based on an energy balance in the fire compartment. This energy balance is expressed by

$$\dot{Q}_{Fire} = \dot{Q}_{Boundary} + \dot{Q}_{Water} + \dot{Q}_{Gas} + \dot{Q}_{Vap} \qquad (1)$$

where

$\dot{Q}_{Fire}$ = Heat release rate of the fire
$\dot{Q}_{Boundary}$ = Heat lost through the walls, ceiling, and *floor*
$\dot{Q}_{Water}$ = Heat absorbed by heating the mist
$\dot{Q}_{Gas}$ = Sensible heat contained in exhaust gases
$\dot{Q}_{Vap}$ = Heat absorbed by evaporation

The following assumptions were made to simplify the calculation:

(i) combustion is complete and takes place entirely within the confines of the compartment (the heat release rate is a constant)

(ii) the temperature is uniform within the compartment at all times (after discharge), and the gases exhausted are assumed to be at the compartment temperature

(iii) a single surface heat transfer coefficient may be used for the entire inner surface of the compartment.

(iv) the heat transfer through the compartment boundaries is unidimensional, i.e., comers and edges are ignored and the boundaries are assumed to be 'infinite slabs'

(v) mist droplets are assumed to be heated to the compartment temperature

The individual components of equation (1) are calculated as follows. The heat release rate of the fire is calculated based on the known fuel spray rate and heat of combustion.

The heat lost through the boundaries of the compartment for preflashover fires can be estimated using an overall heat loss coefficient from preflashover fires [6].

Energy losses by vent gas flow are based on the temperature of the exhaust gases and the exhaust rate determined from the vent flow equation applicable to well stirred compartment environments [7]. Heat lost by evaporation is based on achieving the equilibrium vapor pressure, the vent flow rate, and the heat of vaporization [8]. Heat absorbed by the water mist is determined from the water mist application rate and assuming all mist is heated to the compartment temperature.

If the fire size, the compartment wall area, vent dimensions, and the water flow rate are known, the energy balance can be used to predict the temperature in the space. The predicted temperatures for a wide range of fire sizes are shown in Figure 2. **Also** shown in Figure 2 are the steady-state temperatures measured during the small spray fire tests (<2.0 MW) located on the side of the mockup. **As** shown in Figure 2, the predicted temperatures are within ±7 °C of the temperatures recorded during these tests.

The steady-state oxygen concentration can be calculated considering consumption of oxygen by the fire and displacement of oxygen by water vapor. The limiting oxygen index (LOI) for most hydrocarbon fuels using water vapor as the diluent is between 13-15% [9] (Figure 3). If we select **14%** as the LOI for this approximation, the calculated critical fire size for this compartment, vent configuration, and water flow is 0.9 MW. In this context, the critical fire size is defined as the smallest fire that will produce adequate water vapor to sufficiently dilute the oxygen concentration below the LOI of the fuel and cause extinction. The calculated critical fire size is in agreement with the results of these tests. The water mist systems evaluated during these tests were all capable of extinguishing the 1.0 MW spray fires located on the side of the mockup, but could not extinguish the 0.8 MW fire located on the side of the mockup. Thus, the calculated critical fire size falls in the range identified during these tests.

SUMMARY

A model was developed to predict the effectiveness of water mist system in a known compartment geometry. The model was used to predict the steady-state temperatures and oxygen concentrations of **a** space. The model was validated using the result of the machinery space tests conducted for the USCG. For the compartment geometry and vent size used during these tests (IMO Test Protocol), the model was able to accurately predict the steady-state compartment temperatures during the tests consisting of the smaller spray fires. The larger fires were extinguished before steady-state conditions were reached. This was also predicted by the model. The results of the model were used to accurately predict the smallest fire that will produce adequate water vapor to sufficiently dilute the oxygen concentration to cause extinction. Consequently, fires larger than the critical size would be extinguished while fires smaller than the critical fire size would need to be extinguished by other mechanisms.

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