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COMBUSTION AND FLAME

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Experiments on Extinction of Liquid Hydrocarbon Fires by a Particulate Mineral

T. P. SHARMA, R. S. CHIMOTE, B. B. LAL, and JAGBIR SINGH
Fire Research Laboratory, Central Building Research Institute, Roorkee-247667 (UP), India

A series of experiments on gasoline fires were carried out in a 45-cm-high open-top mild steel tank in the diameter range of 27.5–75 cm in order to study experimentally how efficiently liquid hydrocarbon fires in storage tanks could be extinguished by a particulate mineral. For 30-, 45-, 60-, and 75-cm-diameter tank fires, the minimum thickness of the fire extinction volume of the exfoliated vermiculite required for complete extinction of fires is 16 cm for an average 4.5-mm particle size distribution; further it is a linear tangent function of the minimum fire extinction volume of the exfoliated vermiculite and the size of fire to be extinguished.

INTRODUCTION

Selection of an extinguishing agent and the application technique are the two important primary characteristics of fire extinction. Extinction of a hydrocarbon fire is a phenomenon of challenging magnitude and experience. Recent work by Bilger [1], Gore and Faeth [2, 3], Jeng and Faeth [4], Liew et al. [5], Mitchell et al. [6], Moore et al. [7], Saito et al. [8], Sivathanu et al. [9], and Smyth et al. [10] has shown that there exist state relationships for major gas species in hydrocarbon/air diffusion flames except at the near points of flame attachment and extinction. State relationships differ for each hydrocarbon/air combination and their determination requires tedious and difficult measurements. However, radiation emitted from the flame varies with time even when mean properties are statistically stationary and is a direct manifestation of the nonlinearities that cause mean radiation levels to be biased upward from estimates based on mean scaler properties in the flames. These upward-rising flame radiation fluctuations have been utilized in the present investigation to carry out the fire extinction experiments at an incipient stage of flame growth and development as illustrated in Figures 1 and 2.

The following sections describe the experimental arrangement and the experiments carried out using a particulate mineral as the fire extinguishing agent. The results of the experiments are then discussed.

THE PARTICULATE MINERAL

The particulate mineral, used for carrying out the liquid hydrocarbon open-tank fire experiments, was exfoliated vermiculite. Vermiculite is a geological name given to a hydrated laminar mineral of chemical composition: 39%–45% SiO_2, 14%–20% Al_2O_3, 6%–11% Fe_2O_3–FeO, 1%–2% TiO_2, 15%–20% MgO, 1%–2% CaO, 4%–7% K_2O, 0.5%–1% Na_2O, and 5%–9% H_2O. The exfoliated vermiculite used consists of accordian-like particulates containing millions of minute air spaces, resulting in a high thermal insulation value and low specific gravity; it is a noncombustible, colorless, nonabrasive, rot proof, nonirritant, reflective, moldable, and chemically inert particulate material. It is available in different particle sizes with varying densities. For the approximate particle size < 1.5 mm, its density varies from 128 to 160 kg/m^3; for < 3 mm, it is 88–112 kg/m^3; for < 4.5 mm, it is 72–88 kg/m^3; and for < 6 mm, it is 64–80 kg/m^3. It has a sintering temperature of 1260°C and a melting point of 1315°C.

EXPERIMENTAL SYSTEM

Figure 1 illustrates the experimental arrangement for carrying out the liquid hydrocarbon open-tank fire experiments, using the particulate mineral as the fire extinguishing agent. The experimental system consists of an open-top mild steel tank of

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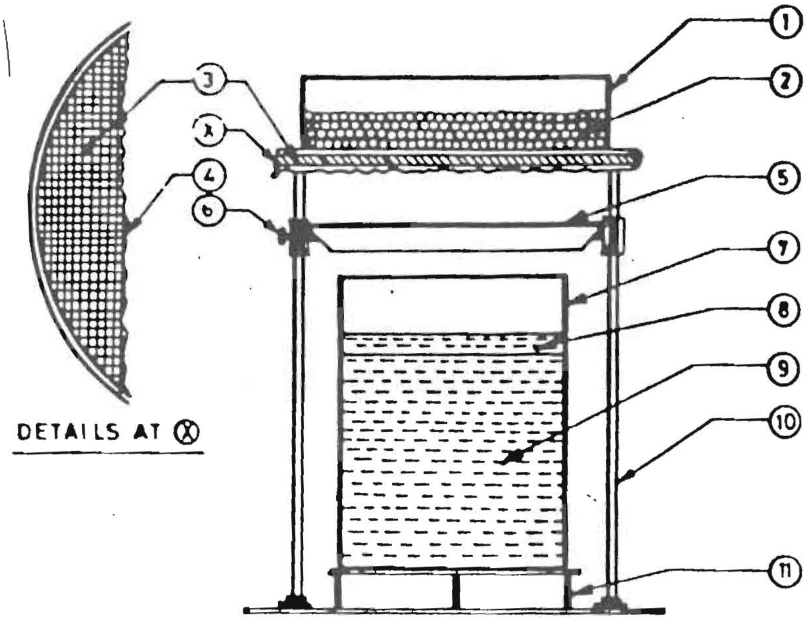


1 METAL CONTAINER
2 EXFOLIATED VERMICULITE
3 25MM X 25MM WIREMESH
4 THERMOSENSITIVE POLYETHYLENE SHEET
5 MOVABLE BARRIER FOR PREBUM TIME
6 SCREW FIXING-CUM-QUICK RELEASE ARRANGEMENT.
7 OPEN-TOP MILD STEEL TANK
8 GASOLINE LAYER
9 ULLAGE (WATER)
10 SUPER-STRUCTURE SUPPORTING COLUMN
11 TANK SUPPORTING STAND

Fig. 1. Experimental setup.

27.5 cm diameter and 45 cm height, placed on a supporting stand, and filled with water to 80% of its total volume as an ullage to the flammable liquid layer. A superstructure made of steel rods and flat metal sheets provides a holder for the exfoliated vermiculite, so allowing its top surface application onto the burning flammable liquid. The holder consists of a wire mesh of 25 mm × 25 mm meshing hole size with a thermosensitive polyethylene sheet fixed along the bottom of the metal container. There is a quick release arrangement allowing control of the preburn time: it consists of a movable metal barrier on the two diametrically opposite superstructure-supporting columns, one-third of the tank diameter above the top of the tank. The height of the wire mesh, vertically above the top of the tank, has been fixed equal to the half of the tank diameter.

EXPERIMENTS

All the experiments were carried out by top surface application of the exfoliated vermiculite, which was achieved automatically by the melting of a thermosensitive polyethylene sheet by the upward rising convected heat currents and flame radiation and/or by the direct flame contact of the flaming fire itself. This was thought to be an effective method of carrying out the extinguishing experiments of open-tank liquid hydrocarbon fires by cutting off the supply of air and fuel vapor to the combustion zone of the fire. Five series of experiments were conducted on gasoline fires. In the first four series, a mild steel tank of 27.5 cm diameter and 45 cm height was used; for the last series of experiments, tanks of 30, 45, 60, and 75 cm diameter were used to study the effect of the size of fire on the volume of the exfoliated vermiculite required for the complete extinction of the fire.

RESULTS AND DISCUSSION

Theories of fire suppression and extinction involve two essential variables: an extinguishing agent and a system or procedure for its application. The method adopted in this investigation with a particulate mineral is the physical isolation of the reducing agent (fuel) in the *wxyz* plane of fuel vapor-oxidizing agent (air) as illustrated in Figure 2. This plane consists of a gaseous mass of flammable mixture, forming the cracking zone for the high-temperature pyrolysis that sustains the diffusion flame of such fires. This zone is critical because if it is physically replaced or manipulated, the fire will be extinguished. The physical isolation of the fuel in the *wxyz* plane was accomplished automatically by the top surface application of the exfoliated vermiculite. This application is initiated by the flaming fire itself by the upward heat convection and flame radiation and/or the direct flame contact causing the melting of the polyethylene sheet. As soon as the polyethylene sheet melts, the exfoliated vermiculite falls freely onto the burning flammable liquid surface through the wire mesh on which the polyethylene sheet had been placed. As the exfoliated vermiculite falls, it passes through the thermal column, combustion zone, and the cracking zone of the fire, finally occupying the space of the fuel vapor-oxidizing agent plane, thus isolating the fuel surface by covering it physically. For extinction, physical covering of the exfoliated vermiculite is critically necessary to create a lightweight, noncombustible, chemically inert particulate blanketing effect so as to cut off the feed of the fuel vapor and air to the combustion zone of the fire, as illustrated in Fig. 2b. Where the phenomenon of momentarily stable residual flames near or at the tank wall side takes place, it has been defined as the partial extinction of fire.

The critical conditions for the exfoliated vermiculite were studied experimentally by selecting the Phase-I variables. The Phase-I variables consist of:

(i) For Fire: Depth of flammable liquid layer, Preburn time, Depth of water (Ullage) and Size of fire;

(ii) For Exfoliated vermiculite: Particle size and Volume.

The Phase II variables consisting of burning rates of liquids, the role played by thermal radiation, and the effects of the tank walls, will be described in a forthcoming paper. The results of the experiments [11] carried out on the Phase 1 variables are graphically represented in Figures 3–7.

Figure 3 shows the variation of the required volume for extinction versus the particle size of the exfoliated vermiculite. At point *a*, partial extinction of fire occurs for 11,000 cm^3 volume of exfoliated vermiculite; below the segment *ac*, no extinction of fire was observed for the vol-

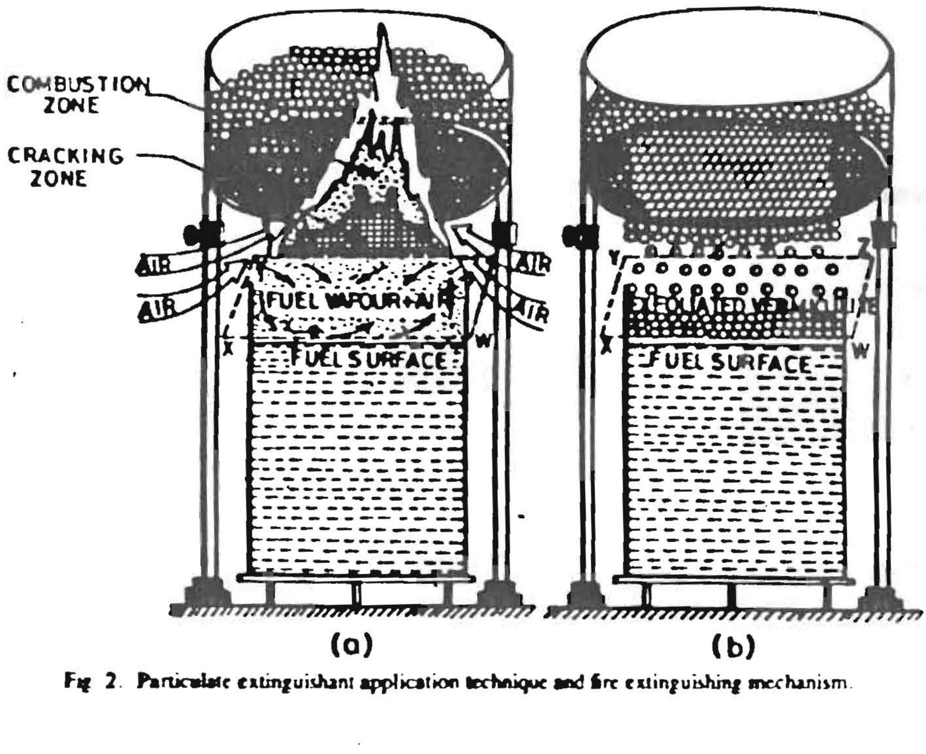


Fig 2. Particulate extinguishant application technique and fire extinguishing mechanism.

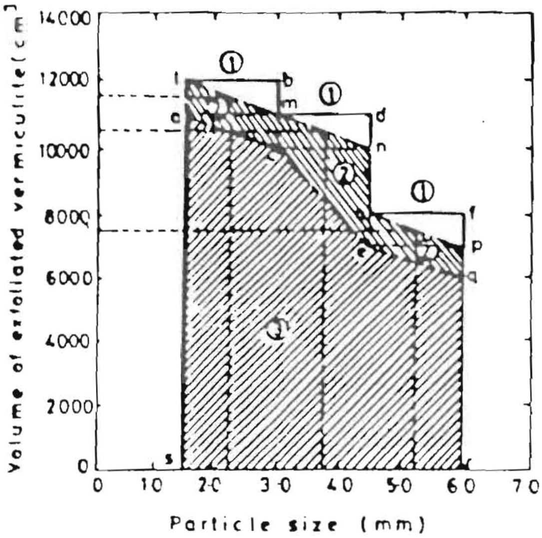


Fig. 3. Experimental volume of exfoliated vermiculite versus particle size.

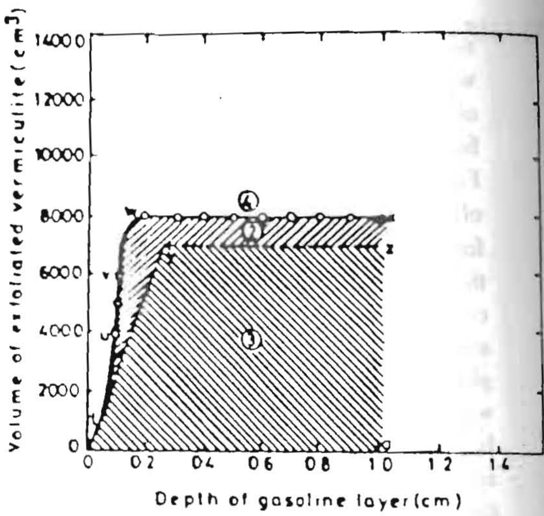


Fig. 4. Experimental volume of exfoliated vermiculite versus depth of gasoline layer.

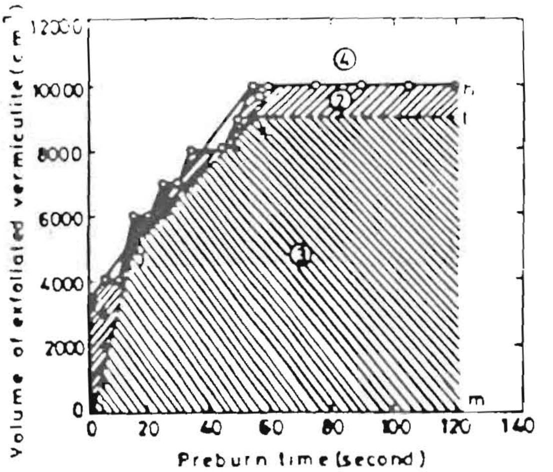


Fig. 5. Experimental volume of exfoliated vermiculite versus preburn time.

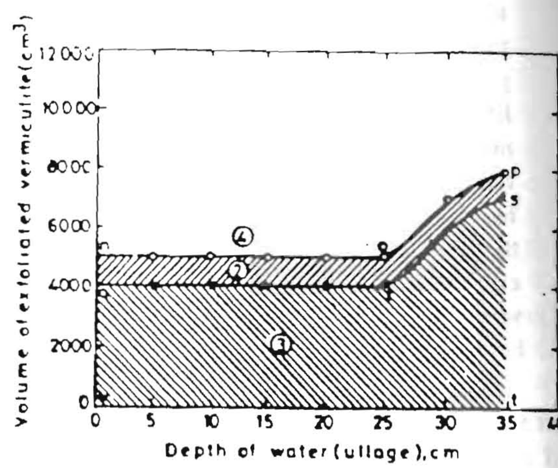
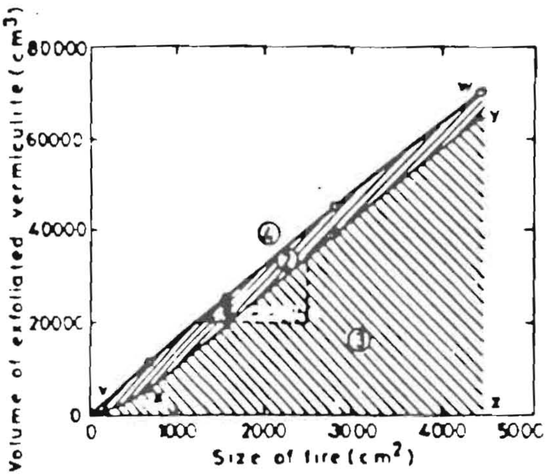


Fig. 6. Experimental volume of exfoliated vermiculite versus depth of water (ullage)



(1) – COMPLETE EXTINCTION

(2) – PARTIAL EXTINCTION

(3) – NO EXTINCTION

(4) – CRITICAL FIRE EXTINCTION CONCENTRATION CURVE

Fig. 7. Experimental volume of exfoliated vermiculite versus size of fire

umes ranging from 1,000 to 11,000 cm^3 for the particle size range of 1.5–3.0 mm. At 12,000 cm^3, a complete extinction of fire was observed; thus the line segments *lb* and *lm* linearly define the minimum and critical fire extinction volumes of the exfoliated vermiculite, respectively, for this size range. Similarly, for the particle sizes 3.0–4.5 mm and 4.5–6.0 mm, the line segments *md* and *mn* and *of* and *op* define the linear relationship for the minimum and critical fire extinction volumes of the exfoliated vermiculite. For the average particle sizes, 2.25, 3.75, and 5.25 mm, the critical fire extinction volumes of the exfoliated vermiculite required for the complete extinction are 11,500, 10,500, and 7500 cm^3, respectively. The points *n* and *o* depict the maximum and critical volumes required for the complete extinction of the fire during its incipient stage for the 4.5–6.0-mm particle size range. Thus for a 1.5-mm shift in particle size range from 3.0–4.5 to 4.5–6.0 mm, there is found to be a drastic decrease in the required volume from 11,000 to 8000 cm^3 as compared with the first 1.5-mm shift in the particle size range from 1.5–3.0 to 3.0–4.5 mm. Thus the exfoliated vermiculite of average particle size range of 3.75–5.25 mm is the most effective. For this reason, an average particle size of 4.5 mm was chosen for the exfoliated vermiculite used in the consequent series of fire experiments. The triangles *lbm*, *mdn*, and *ofp* are the regions of complete fire extinction volumes for the particle sizes in the range of 1.5–3.0, 3.0–4.5, and 4.5–6.0 mm, respectively.

Figure 4 shows the variation of the experimental volume of the exfoliated vermiculite versus the depth of gasoline layer. In the first instance, a 0.1-cm depth of gasoline layer was used as the initial depth over the column of water ullage with a preburn time of 45 s for fire development followed by extinction using different volumes of the exfoliated vermiculite. For volumes of 4000, 5000, and 6000 cm^3, the fire was seen to be completely extinguished, with extinction times of 4, 3, and 2 s, respectively. The extinction of a 0.2-cm depth-of-gasoline-layer fire occurred at 8000 cm^3, and this volume of exfoliated vermiculite was found experimentally to be the critical amount for all depths of gasoline layer ranging from 0.2 to 1.0 cm; below this volume the partial extinction of fire occurs critically up to 7000 cm^3. Thus the curve *tyz* is the curve of critical partial fire extinction volumes and *tuvwx* is a critical fire extinction volume curve. The *tyzo* region represents the conditions of No fire extinction.

Figure 5 shows the variation of the experimental volume of exfoliated vermiculite versus preburn time. For preburn times up to 55 s, the volume of exfoliated vermiculite required for the complete extinction of fire increases up drastically from 4000 to 10,000 cm^3. The most critical fire extinction volume for the exfoliated vermiculite was 8000 cm^3 because at this volume the partial extinction of fire was observed to be very close to the "no extinction" volume; this was the reason to select a 45-s preburn time as an appropriate preburn time for the series of experiments where this parameter was constant. For the preburn times above 55 s, the critical fire extinction volume was found to be constant, and for the preburn times ranging from 55 to 120 s, it works out to be 10,000 cm^3. The segment *fg* thus shows graphically a least squares straight line of the critical fire extinction volume required for the complete extinction of a fire. The dotted line *ijkl* depicts the critical partial fire extinction volumes. It is critical because, below this *ijkl* curve, there exists a region *ijklm* of "no extinction" of fire.

Figure 6 shows the effect of the depth of water (ullage) on the volume of exfoliated vermiculite. The gasoline fire experiments were carried out with a constant volume of gasoline by varying the depth of water (ullage) from 35 to 5 cm. The maximum depth of 35 cm was selected on the basis of the consideration that in any flammable liquid storage tank, the maximum permissible volume of flammable liquid to be stored is 80% of its total storage capacity, which is 35 cm for a 45-cm-high experimental tank. This leaves a 1-cm working space for different depths of the gasoline layer from 0.1 cm. With a 35-cm depth of water ullage, the partial extinction of fire occurs at 7000 cm^3, and the extinction at 8000 cm^3. Later, a decreasing trend in the volume of the exfoliated vermiculite was observed for every gradual decrease in the depth of water ullage. The line segments *nop* and *qrs* define the curves of critical and partial fire extinction volumes for all the depths of water ullage; and the region *qrstu* is the region of "no fire extinction." Thus, 5000 cm^3 can be taken as the minimum fire extinction volume of the exfoliated vermiculite for a half-filled gasoline storage tank of size 27.5 cm diameter and 45 cm height. For the same size tank filled more than half and up to the maximum permissible flammable liquid storage level limit, 5000 cm^3 can be taken as the minimum fire extinction volume of the exfoliated vermiculite.

Figure 7 shows variation of the experimental volumes required to extinguish the different size of fires. For 30-, 45-, 60-, and 75-cm-diameter tank fires of size 707, 1591, 2828, and 4418 cm^2, complete extinction of fire occurs at 10,000, 25,000, 45,000, and 70,000 cm^3 volumes of the exfoliated vermiculite, respectively. The segment vw thus represents the critical fire extinction volume curve for the different sizes of fire; and the slope of the curve defines the minimum thickness required for the complete extinction of the fire by physical covering. Further, it is a linear tangent function of the critical fire extinction volume of the exfoliated vermiculite and the size of fire to be completely extinguished. The value $\tan\phi$ of the curve works out to be 16, which, as a matter of fact, is the minimum thickness of the volume of exfoliated vermiculite required for the complete extinction of fire. If this $\tan\phi$ value satisfies further linearly, then for any flammable liquid storage tank of diameter D m, the minimum fire extinction volume of the exfoliated vermiculite required for the complete extinction of a gasoline fire could be $0.125D^2$ m^3. Further experiments are in progress for the validation of this mathematical relation. Analysis of data to determine whether these results can be scaled up to tanks large enough to be of practical significance is presented in another paper.

CONCLUSIONS

An experimental study with a particulate mineral has experimentally demonstrated the suitability of the exfoliated vermiculite as a particulate fire extinguishing agent for flammable liquid tank fires. The important conclusions of the study are as follows: The fire extinguishing effectiveness of the exfoliated vermiculite is a maximum for an average particle size range of 3.75–5.25 mm. For the extinction of a completely filled (80% of its total volume) gasoline tank fire of about 600 cm^2 size with a preburn time of 45 s, the critical volume of exfoliated vermiculite is 8000 cm^3. Further, the depth of water (ullage) below 70% does not have any significant effect on the volume requirement of the exfoliated vermiculite for the extinction of the fire. For up to 4500 cm^2 size of flammable liquid tank fire, a minimum 16 cm thickness of the exfoliated vermiculite is required for the complete extinction of the fire.

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