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Experimental study on ceiling gas temperature and flame performances of two buoyancy-controlled propane burners located in a tunnel

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HIGHLIGHTS

- Experiments were conducted for two energy sources burning in a model tunnel.
- Energy release rate and burner spacing were varied.
- Flame merging criteria in tunnel were proposed.
- Correlations for estimating the ceiling gas temperature profiles were developed.
- The interacting flame lengths in tunnel were compared with the open space.

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ABSTRACT

Multiple energy sources in a tunnel might lead to merge of flames with small enough spacings, releasing more heat and pollutant emissions than a single energy release source in tunnel and thus posing a great threat to tunnel structure, facilities and trapped people. As the heat detection, controlling and cooling systems are originally designed for the single energy release source, while the spacing between energy sources in tunnel is changeable and unpredictable. Then it is important and helpful to research on the much different characteristics of multiple energy sources with interacting ceiling flames for effective control the high risk scenarios. This paper aims to study the ceiling gas temperature profile and flame properties induced by two interacting energy sources in tunnel so as to improve the understanding of the arrangement of heat detectors and water sprinklers in tunnel. Two identical propane burners were used as energy sources located in a longitudinal array in tunnel. The total energy release rate and burner spacing were varied. The flame merging probability, ceiling gas temperature, vertical flame height and longitudinal flame extension were measured. The criteria of beginning merging and fully merging of flames are respectively proposed for two energy sources in tunnel. Results showed that the area of ceiling flame region increases with higher energy release rate. Models for predicting the ceiling gas temperature profiles induced by two energy sources in tunnel are established respectively for weak and strong plumes impinging on the ceiling. A modified model for predicting the combined vertical and longitudinal flame lengths from two burners in tunnel is proposed involving the normalized energy release rate, burner size and spacing. Finally, the comparison between models proposed for ceiling gas temperatures and flame lengths in tunnel and other configurations identifies the high risk of multiple energy sources in tunnel.

1. Introduction

Two or more flames burning interactively is termed as multiple flames. In the past decades, most studies on multiple flames were conducted in open space. The key parameter involved in multiple flames is spacing [1] as the flames might lean to each other and merge if sufficiently close [2]. Flame merging is believed as more destructive and uncontrollable [3]. Finney and McAllister [4] reviewed the empirical merging criteria for multiple flames derived in open space. As a typical confined space, tunnel might involve multiple vehicles burning simultaneously caused by collisions or subsequent accidents [5]. Generally, there are many mechanical and electrical facilities in tunnels, such as heat detectors and sprinklers. When the uncontrollable energy along with

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Nomenclature

b	plume radius at ceiling level, where the velocity is one-half of the centerline value (m)
c_p	specific heat of air (kJ/(kg·K))
D	energy source diameter/length (m)
g	gravitational acceleration (m/s^2)
H_{ef}	ceiling height above the burner surface (m)
L_B	impingement point induced by burner B to the center of burner B (m)
L_{ef}	effective flame length (m)
L_f	flame height (m)
N	flame number of $N \times N$ array
P	perimeter of air entrainment (m)
P_m	flame merging probability
$\dot{Q}$	energy release rate of a single flame (kW)
$\dot{Q}_c$	convective energy release rate (kW)
$\dot{Q}_D^*$	dimensionless energy release rate for each individual burner
$\dot{Q}_g^{*\prime}$	dimensionless energy release rate for group flames
$\dot{Q}_{total}$	total energy release rate of two burners (kW)
r	radial distance from the flame axis and/or impingement point (m)
r_B	horizontal distance from the center of burner B (m)
r_f	distance from the impingement point to the flame tip in the downstream of burner B (m)
S	burner spacing (m)
T	gas temperature (K)
T_∞	ambient temperature (K)
ΔT	temperature rise (K)
$\Delta T_{\max}$	maximum temperature rise at impingement zone (K)

Greek symbols

α	power value of $\dot{Q}^*_{DH_{ef}}$ in Eq. (4)
ρ_∞	ambient density (kg/m^3)

enormous pollutant emissions and high temperatures induced by flame and smoke are released to a tunnel, the facilities within the tunnel should be activated simultaneously to achieve quick energy detection, controlling and cooling. Optimizing installation spacing of heat detectors and sprinklers could improve the effectiveness of energy controlling at the early burning stage. As a matter of fact, in many tunnel accidents, two or more crashed vehicles were burnt simultaneously [6], the resultant merging flames will release more heat and pollutant emissions than a single vehicle accident in tunnel. And as the spacing between the crashed vehicles in tunnel is changeable and unpredictable, it will dramatically increase the difficulty of quick heat detection and cooling. However, little effort has been paid attention to multiple flames in tunnels and so far no merging criterion is proposed for multiple flames in tunnel. This paper attempts to bridge this knowledge gap.

Gaseous and liquid fuels were commonly used as energy sources in free and confined spaces [7]. For multiple liquid flames in open space, Huffman et al. [8] and Liu et al. [9] found that the heat release rate (HRR) developed a non-monotonous trend with decreasing the burner spacing due to the competition between heat feedback enhancement and air entrainment restriction. Since the HRR of liquid sources is strongly affected by the radiation from flame and smoke, it is difficult to quantify the effect of spacing. On the other hand, gas burners are affected only by the fuel flow rate while the impact of heat feedback is insignificant [10]. Therefore, the gas burners were used as energy sources in former studies [3,10–14]. When flame height is smaller than the ceiling height, the ceiling jet is a weak buoyant smoke flow. Fukuda et al. [3] concluded that when the HRR of each burner is low, the flames in a square array are hardly merging and the free flame height is little affected by the spacing. Gao et al. [14] found that if the flame tip did not hit the ceiling the flame height from a single energy source in tunnel is almost the same as the one in free space. When the free flame height is equal to or exceeds the ceiling height above the fuel surface, the resultant ceiling jet is driven by a strong plume. It was found that the pollutants emission from an impinging flame is a crucial behavior of the flame and the emission characteristics of impinging flames might differ from that of the same energy source in open space [15–17]. As strong plume hit the ceiling with flames spread radially along the ceiling, the gas temperature and the resultant heat flux received by the ceiling will increase dramatically and the risk of flame propagation enhances [18]. Estimations of the temperature field and flame length can facilitate determinations on the heat transfer from energy sources to receiving mediums such as the ceiling, nearby objects and secondary fuels [19]. In addition, the study of highest temperatures under a ceiling is significant since it has a great impact on the arrangement and activation of sprinkler systems in tunnels [20]. Alpert [21] and Heskestad and Hamada [22] proposed a set of correlations, which have been widely used, for predicting the maximum temperature decay profiles for both weak and strong plumes induced by a single source under unconfined ceilings. However, whether these correlations are suitable for multiple flames in tunnel is unclear. In spite of numerous studies focused on the free flame height of multiple energy sources [2,3,12,13,23,24], limited physical model is developed to predict the interacting flame length in tunnel.

The objective of this work is to understand the ceiling gas temperature and flame behaviors from two propane burners located along the longitudinal centerline of tunnel. The total energy release rate and burner spacing were varied to quantitatively study the flame merging behaviors. Attempts have also been made to develop empirical models to predict not only the longitudinal ceiling gas temperature profile but also the flame length. The current study will provide beneficial scientific supports to the optimal arrangements of heat detectors and sprinklers, resulting in high efficiency of energy detecting and cooling as well as achieving optimum energy controlling.

2. Experiments

Fig. 1 shows the experimental setup. The experiments were conducted in a 1/6-scale model tunnel which is 6 m long, 2 m wide and 0.86 m high. Fireproofing boards of 20 mm thick were used to make the top, bottom and one sidewall of the tunnel while the other sidewall was made of 10 mm thick fire-resistant glass for observation. The left and right ends of the tunnel were opened for natural ventilation. Two square gas burners denoted as A and B with a side length (D) of 15 cm were located at the longitudinal centerline with 22 cm higher than the tunnel floor. Propane was used as the fuel with different HRRs adjusted using a flow meter. The heat of combustion of propane was 46.3 MJ/kg and the combustion efficiency was assumed to be unity [25]. In the experiments, 6 HRRs ($\dot{Q}_{total}$) were used including two burners, which are 21.6, 43.2, 64.8, 86.4, 108.0 and 129.6 kW, while the respective HRR ($\dot{Q} = \dot{Q}_{total}/2$) of burners A and B can be

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