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Similarity study of smoke movement from photovoltaic panel roof fire with wind effect

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SUMMARY
With the large-scale installation of Photovoltaic (PV) panels increased by 7 times in the past 10 years, the number of fires caused by PV is also increasing rapidly. However, the relevant fire studies are deficient. Therefore, it is required to study the mechanism of smoke movement from PV panel roof fire with wind effect, moreover, the wind tunnel test is a popular method. This study provides a method to use helium release to replace the real fire smoke with the new similarity law in the non-fire-proof wind tunnel and conducts a series of wind tunnel tests with flat and sloped roof angles. The proposed theory is derived from the Jet theory under the wind effect. Furthermore, the effective change in the acceleration of gravity is applied due to buoyancy force, i.e. reduce gravity. The results show that the proposed method is justified by comparing the simulation results between the sub-scale helium model and full-scale smoke model with a 5.53% (velocity) and 11.52% (dimensionless temperature/concentration) difference.

Keywords: FDS, wind tunnel, helium test

1. INTRODUCTION
With the widespread use of photovoltaic (PV) panels worldwide, correspondingly, the number of fires from PV roofs is dramatically rising. However, the relevant fire studies are deficient and the wind tunnel test is a popular method. Therefore, this study proposed a new scaling method based on the jet theory for the helium wind tunnel test to investigate the mechanism of smoke spread from PV roof fire under the wind effect. The helium wind tunnel test replaces the real fire plume with the helium release. The fire dynamics simulator (FDS) models are built in full-scale (fire) and 1/15 sub-scale (helium) in the wind tunnel. The results in transient and steady states are compared to justify the proposed scaling method.

2. METHODOLOGY
2.1 SCALING METHOD OF FIRE PLUME UNDER THE WIND EFFECT
To obtain the relationship between the sub-scale model and full-scale models, the plume is considered as a jet stream and the momentum is conserved as Figure 1.

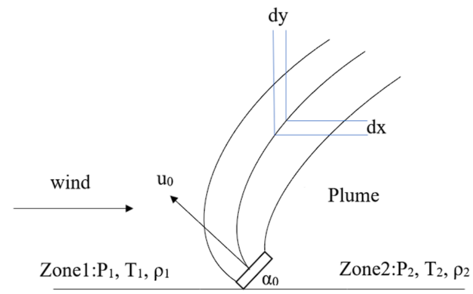

Figure 1. Plume of fire/helium induced at angle α under the wind effect.

The following equation can be found (Hayes, 1968):

$$\left(\frac{\Delta p}{\frac{\rho u_0^2}{g'}}\frac{x}{b_0}+sin\alpha_0\right)^2+\left(\frac{\Delta p}{\frac{\rho u_0^2}{g'}}\frac{y}{b_0}-cos\alpha_0\right)^2=1 \tag{1}$$

where Δp is the pressure difference between zones 1 and 2, $g'=\frac{g\Delta\rho}{\rho_a}=\frac{g(\rho_0-\rho)}{\rho_a}$ is reduce gravity to combine the gravity and buoyancy forces, ρ is the density, u_0 is the initial velocity of the plume, b_0 is the width of the plume area, α_0 is the angle of the plume, and x, and y are the coordinates of the fire plume centerline. A new dimensionless number is obtained:

$$\frac{\Delta p}{\frac{\rho u_0^2}{g'}}=\frac{wind\ effect}{buoyancy\ effect} \tag{2}$$

where Δp represents the wind effect term and $\rho u_0^2/g'$ represents the buoyancy term.
The dimensionless heat release rate (HRR), $Q*$ is mentioned by Zukoski (Zukoski, 1986):

$$Q^*=\frac{Q}{\rho_\infty c_p T_\infty\sqrt{g}l^{\frac{5}{2}}} \tag{3}$$

Therefore, the scale of the heat release rate is:

$$Q_s=Q_f(\frac{L_s}{L_f})^{\frac{5}{2}} \tag{4}$$

where subscripts *s* and *f* represent the sub-scale and full-scale models.
The equation of convective heat release rate can be expressed as:

$$Q_c=\rho_{smk}C_pAu_0(T_{smk}-T_a) \tag{5}$$

where Q_c is convective HRR, *A* is the area of the fire, $q_{smk}=Au_0$, *q* is the volume flow rate.
When density ρ_{smk} and temperature T_{smk}, T_a are conserved, the following scales can be found:

$$u_{0-s}=u_{0-f}\sqrt{\frac{L_s}{L_f}} \tag{6}$$

$$\Delta p_s=\Delta p_f\frac{L_s}{L_f} \tag{7}$$

$$u_{wind-s} = u_{wind-f}\sqrt{\frac{L_s}{L_f}} \tag{8}$$

$$t_s = t_f\sqrt{\frac{L_s}{L_f}} \tag{9}$$

2.2 SIMILARITY BETWEEN FIRE PLUME AND HELIUM PLUME

The convective heat release rate can be described by the volume release rate of helium (Zhao & Wang, 2014):

$$q_h = \frac{Q_c}{C_p T_a(\rho_a - \rho_h)} \tag{2}$$

The helium is mixed with the surrounding air. The relationship between smoke temperature and helium volumetric fraction can be expressed as:

$$T^* = \left(\frac{T_{smk} - T_a}{T_a}\right) = \chi_h\left(\frac{\rho_a - \rho_h}{\rho_a}\right) \tag{1}$$

where χ is the volumetric fraction in mol/mol.

2.3 SUMMARY OF SIMILARITY METHOD BETWEEN FULL-SCALE SMOKE AND SUB-SCALE HELIUM MODELS

By combining the equations in sections 2.1 and 2.2, a similarity relationship between full-scale smoke and sub-scale helium models (1/15 scale) can be concluded in Table 1:

Table 1. Summary of similarity method

Parameters	Relation
Geometry	$l_{s,h} = \frac{l_{f,smk}}{15}$
Time	$t^* = \frac{t_{s,h}}{\sqrt{L_s}} = \frac{t_{f,smk}}{\sqrt{L_f}}$
Wind speed	$u_{s,h,w} = u_{f,smk,w}\left(\frac{L_s}{L_f}\right)^{0.5}$
Volume flow rate of helium / HRR	$q_{s,h} = \frac{Q_{c,f,smk}(\frac{L_s}{L_f})^{\frac{5}{2}}}{C_p T_a(\rho_a - \rho_h)}$
Velocity	$u^* = \frac{u_{f,smk}}{u_{f,smk,w}} = \frac{u_{s,h}}{u_{s,h,w}}$
Dimensionless temperature/ concentration	$T^* = \frac{T_{f,smk} - T_a}{T_a} = \chi_{s,h}\left(\frac{\rho_a - \rho_h}{\rho_a}\right)$

4. RESULTS

The full-scale fire smoke model and sub-scale helium model (1/15) are built in FDS in the wind tunnel as shown in Figure 2 (left), and the PV fire is replaced by the helium release. The transient state results in the room of dimensionless temperature in full-scale and dimensionless helium concentration in sub-scale are compared and obtain a good agreement with a 16.5% discrepancy.

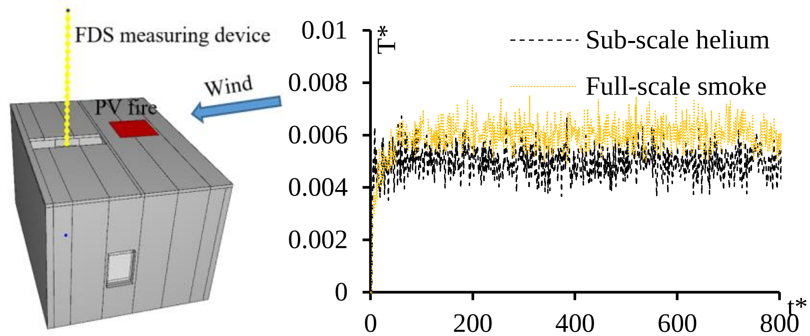

Figure 2. left: Schematic view of building models in FDS; right: Comparison simulation results of average temperature between sub-scale helium and sub-scale smoke in transient state.

Figure 3 illustrates the magnitudes of dimensionless velocity and temperature/concentration with FDS measuring devices. The theory can be justified by 5.53% (velocity) and 11.52% (dimensionless temperature/concentration) discrepancies.

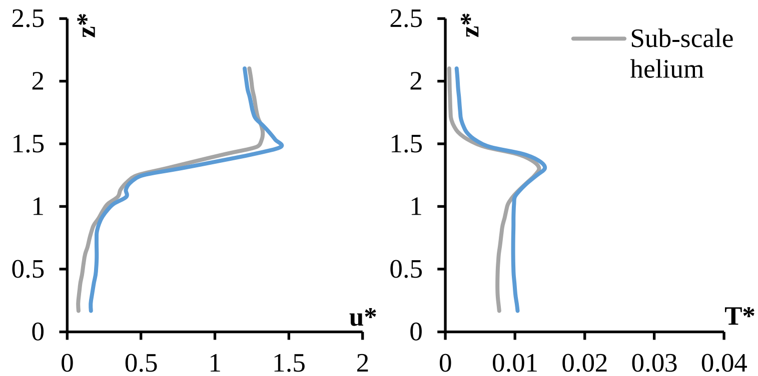

Figure 3. Comparison simulation results of dimensionless velocity, *u**, between sub-scale helium and sub-scale smoke in steady state.

4. CONCLUSIONS

The novel scaling method and dimensionless number are developed to investigate the smoke spread on the PV fire. The simulation of FDS is run and the results obtain a good agreement between the full-scale smoke model and sub-scale helium model with 5.53% (velocity) and 11.52% (dimensionless temperature/concentration) discrepancies.

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