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Thermal analysis of reinforced concrete chimneys with fiberglass plastic liners in uncontrolled fires

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ABSTRACT

This paper presents a simple method to calculate fire duration and flue gas temperatures for reinforced concrete (RC) chimneys with fiberglass reinforced plastic (FRP) liners based on experimentally determined burning characteristics of the liner material. Implementation of the method to calculate fire durations and the transient heat transfer conditions is demonstrated for single- and four-liner chimneys. A parametric study is carried out for chimney designs and geometries ranging from 100 m to 300 m in height and 7 m to 40 m in diameter, with 1–4 liners and varying opening configurations. The results are used to identify a limited number of cases for which the RC chimney undergoes the most extreme reduction in its post-fire residual strength. Analytical estimations of the chimney residual strength after the fire are obtained using a method established based on the procedure outlined in the American Concrete Institute (ACI) 307 Standard for chimney strength calculations. Calculations for a series of critical configurations of RC chimneys, with FRP liner geometries within the practical design limits detailed in this paper, show that the post-fire structural capacity of the chimneys would not lead to catastrophic failures especially because the chimney is not expected to see other high design lateral loads such as wind or earthquake simultaneously.

1. Introduction

Fiberglass reinforced plastic (FRP) liners, schematically shown in Fig. 1, are used to protect the shell of reinforced concrete (RC) chimneys from the corrosive effects of the flue gases. The FRP material is combustible and employment in concrete chimneys increases the risk of uncontrolled fire. Smoking or hot work inside the chimney during maintenance, ignition of stored flammable materials at the base of the chimney or some abnormal condition in the upstream system could lead to a fire in the FRP liner. In March 2006 a fire occurred in a reinforced concrete chimney of a power plant that was being retrofitted with an FRP liner [1]. Reports mention that the fire spread to all but the top 3 m of the 300-m high chimney. The fire broke out at night and was fully extinguished by the afternoon of the following day. Though the fire destroyed the liner, the concrete chimney did not collapse. Even though there have been no major collapse-following-fire incidents, the effects of a liner fire and the possibility of chimney collapse need to be investigated due to the expanding usage of FRP liners in reinforced concrete chimneys.

Knowledge of the fire characteristics is essential in estimating the reduction of structural capacity of the chimney during the fire, as well as its post-fire residual strength because, in general, prolonged exposure of the chimney shell to high temperatures will degrade the concrete strength and depending on the level and duration of exposure it can jeopardize the structural integrity of the RC chimney [2–10]. To study the thermal behavior of RC chimneys with FRP liners, three fire scenarios, shown schematically in Fig. 1, were considered:

- The first scenario covers burning of a pile of FRP rubble created by a fire that started on the liners and caused them to collapse at the bottom of the RC chimney. Assuming that the chimney's bottom opening that allows the incoming airflow is not closed or blocked during the fire, it is expected that the incoming air will push the flames towards one side of the chimney causing localized heating of the chimney wall.
- In the second scenario, the FRP remains structurally sound during a fire outside a liner or liners. Part of the heat released by such a fire will be carried out of the chimney by the air flowing between the liner and the concrete shell, and part of it will heat up the chimney wall. The average surface area of the FRP that is involved in the fire at any given time affects the duration of the

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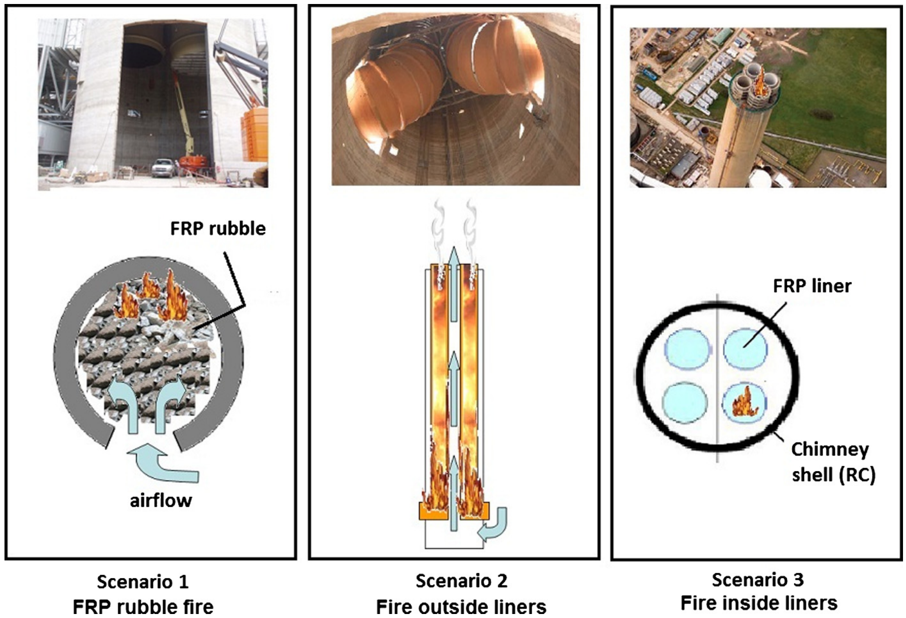

Fig. 1. Fire scenarios for chimneys with FRP liners.

fire as well as the average temperature increase of the air flowing through the chimney. If the liner breaks and causes "blockage" of the airflow, it is conceivable that less air will flow through the chimney and the concrete wall will be exposed to higher average gas temperatures. In studying this scenario, it was conservatively assumed that even for restricted airflow conditions, there is enough oxygen for well-ventilated burning.

- Fire in the third scenario develops and propagates inside a liner or liners without penetrating to the outside and without liner collapse. In this case, the fire is contained within the liner and the air in the gap between the liner and the concrete wall does not experience any major temperature increase. Thus, this scenario is unlikely to cause considerable reduction in chimney strength and is not analyzed further.

2. Outline of approach

The main objective was to determine the reduced structural capacity of the critical chimney and fire configurations, and check if chimneys with FRP liner geometries that are within the practical design limits will have enough post-fire residual capacity to carry the design loads. This requires a stress analysis procedure summarized in Section 8 using a method [11], established based on the analyses outlined in the ACI 307 Standard [12]. The stress analysis required ways to calculate the average fire duration and the average temperature of the gas inside the chimney, discussed in Sections 4 And 5, respectively, established based on burning characteristics of the FRP liner material determined experimentally as described in Section 3.

The approach was applied, as presented in Section 6, to two cases of transient heat transfer analyses across the concrete wall for 165-m high single-liner and 240-m high four-liner chimneys. Schematics of the two chimneys with representative dimensions are shown in Fig. 2. Extensive parametric studies for chimney geometries ranging from 100 m to 300 m in height and 7 m to 40 m in diameter, with multi liners and varying opening configurations were performed to identify critical configurations based on the severity of the fire conditions. They are described in Section 7.

3. Burning characteristics of FRP liner material

An experimental study of a salvaged chimney liner showed that this material burns, a illustrated in Fig. 3, in two stages: an initial rapid flare-up of the resin-rich top layer (stage I) followed by a die-back to a steady-state lower intensity fire (stage II).

The average heat release rate per unit area of the liner material for the duration of the fire, $\bar{\dot{q}}''$ (kW/m^2), can be calculated as a time weighted average by Eq. (1).

$$\bar{\dot{q}}'' = \frac{\frac{\dot{Q}_I}{A_I} \cdot t_I + \frac{\dot{Q}_{II}}{A_{II}} \cdot t_{II}}{t_I + t_{II}} \quad (1)$$

The symbols $\dot{Q}$ and A in Eq. (1) correspond to the net heat release rate (kW) and the burned area (m^2) respectively, while t is the duration of each burning phase (s), and subscripts I and II correspond to the two stages of burning. The test data used to calculate average heat release rates for three Parallel Panel [13,14] experiments based on Eq. (1) are shown in Table 1.

The efficiency of FRP combustion was quantified in terms of an effective heat release parameter $\Delta H_{c,PP}$ (kJ/kg). As shown in Eq. (2), this parameter depends on the average heat release rate per unit area of FRP for the duration of the fire, $\bar{\dot{q}}''$, which is calculated by Eq. (1), the duration of the two burning stages t_I and t_{II} (s), the FRP thickness X (m) and density ρ (kg/m^3).

$$\Delta H_{c,PP} = \frac{\bar{\dot{q}}'' \cdot (t_I + t_{II})}{X \cdot \rho} \quad (2)$$

The FRP thickness used in the experiments was X = 1.58 cm, which is a typical thickness of industrial FRP liners (1.3–2.5 cm or 0.5–1.0 in.) [15]. The density of FRP was ρ = 1678 kg/m^3.

Data used for the calculation of the effective heat release parameter are also given in Table 1. For the purposes of this study the calculated values of the average heat release rate per unit area of the liner material for the duration of the fire and the effective heat release parameter were rounded up to representative values of $\bar{\dot{q}}'' = 75$ kW/m^2 and $\Delta H_{c,PP}$ = 8 MJ/kg, respectively. These values are consistent with published data [16].