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Wall and Corner Effects on Fire Plumes as a Function of Offset Distance

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Abstract. A series of compartment fire experiments is described in which a square natural gas burner was positioned in a corner or against a wall and gradually moved towards the room center to assess the relative effects on the plume and compartment temperatures. The experiments were conducted to validate computational fluid dynamics simulations that were performed to provide guidance for probabilistic risk assessments in nuclear power plants. The measurements consist of one dimensional vertical thermocouple arrays to measure the hot gas layer temperature and height, and a three dimensional thermocouple array to measure the temperature of the fire plume as the burner is moved away from the corner or wall. As a result of the modeling and experiments, recommendations have been made that quantify wall and corner effects as a function of offset distance.

Keywords: Fire plumes, Wall effects, Corner effects

1. Introduction

In performing probabilistic risk assessments (PRA) of nuclear power facilities, plant engineers and consultants make use of various empirical correlations to estimate potential damage to critical safety equipment in the event of a fire. One of these, Heskestad's plume correlation [1], has been supplemented by a so-called "location factor," k_F, that accounts for the change in plume behavior if the fire is against a wall or in a corner. The idea behind this modification, first proposed by Zukoski et al. [2], is that a wall or corner fire plume is assumed to behave as if it were "mirrored" in the wall or corner with $k_F = 2$ or $k_F = 4$ times its base area and heat release rate, respectively. Based on this assumption, the Heskestad correlation for centerline plume temperature rise, $\Delta T_0(z)$, is modified as follows:

$$\Delta T_0(z) = 9.1 \left(\frac{T_\infty}{g\, c_p^2\, \rho_\infty^2} \right)^{1/3} \left(k_F \dot{Q}_c \right)^{2/3} (z - z_0)^{-5/3} \qquad (1)$$

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Here T_∞ is the ambient temperature, g is the acceleration of gravity, c_p is the specific heat of air, ρ_∞ is the ambient air density, $\dot{Q}_c$ is the convective heat release rate, z is the height above the fire, and z_0 is the "virtual" origin, given by

$$\frac{z_0}{D_F} = -1.02 + 1.4\,\dot{Q}^{*\,2/5}; \quad \dot{Q}^* = \frac{k_F \dot{Q}}{\rho_\infty\, c_p\, T_\infty \sqrt{g\, D_F}\, D_F^2} \tag{2}$$

Here, D_F is the diameter of the "mirrored" fire base, $D_F = \sqrt{k_F} D$, where D is the diameter of the actual fire, and $\dot{Q}$ is the total heat release rate of the actual fire.

Heskestad [1] and Lattimer and Sorathia [3] provide a number of references to studies that seek to develop correlations for flame heights and plume temperatures of wall and corner fires. A number of these studies suggest that the location factors given above may be overly "conservative;" that is, may over-estimate the impact of a wall or corner on plume temperature and entrainment rate. Consequently, the U.S. Nuclear Regulatory Commission's Office of Research (NRC) and the Electric Power Research Institute (EPRI) undertook a joint study [4] to determine (1) appropriate values for the location factors, and (2) the distance from the wall or corner at which their effect becomes insignificant. In other words, what constitutes a fire being "in the corner" or "against a wall"?

Williamson, Revenaugh et al. [5] considered the effect of separation distance between the fire and a corner, but they were mainly interested in its influence on the heat flux to the wall and they only considered distances of 0 cm, 5 cm, and 10 cm. Dembsey et al. [6] considered the effect of the fire's location on the overall thermal environment of the room, but their study was limited only to fires in the center of the compartment or against a wall. No studies to date have been performed to quantify the fire severity as a function of the distance from wall or corner to room center. To this end, EPRI and the NRC used the computational fluid dynamics model fire dynamics simulator (FDS) to simulate dozens of fire scenarios where fires of different sizes were placed at various locations relative to a wall or corner. At the time of the study, FDS had not been formally validated for this application, and NIST was asked by the NRC to perform validation experiments.

This short communication focuses solely on the validation experiments to support the work done by the NRC and EPRI. These experiments were not intended to cover the wide range of possible fire scenarios, but rather assess the accuracy of the model. Details of the NRC/EPRI modeling study are summarized in Ref. [4] and details of the validation of FDS for these experiments can be found in Ref. [7]. The full report of the experiments is given in Ref. [8]. A link to the data files is given in the report.

2. Experimental Description

The experiments were conducted in the summer of 2017 at the National Fire Research Laboratory at the National Institute of Standards and Technology in Gaithersburg, Maryland. The test compartment was 11.0 m (36 ft) long, 7.0 m

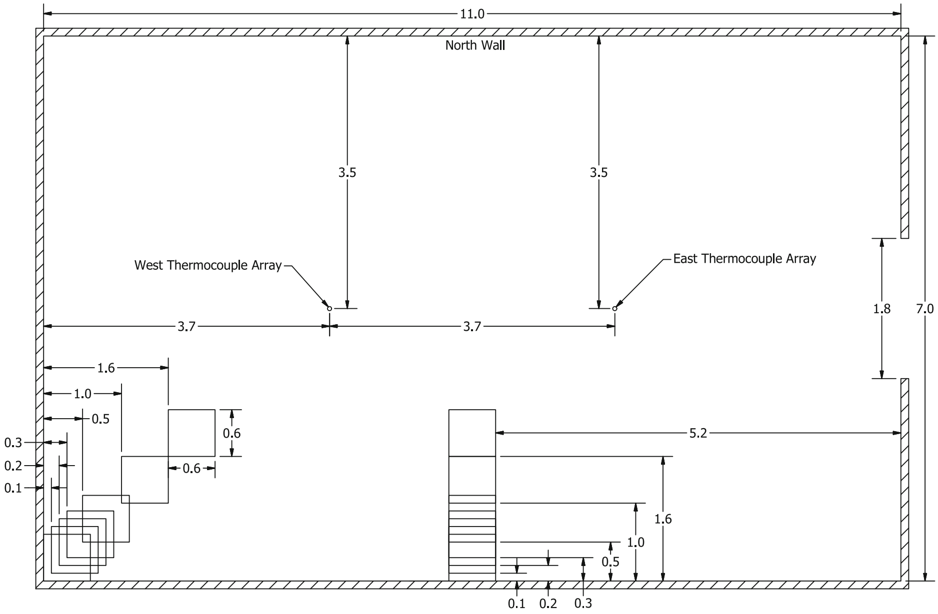

Fig. 1. Plan view of the compartment showing locations of the corner and wall burners. All dimensions are in meters. The height of the compartment is 3.8 m (12.5 ft).

(23 ft) wide, and 3.8 m (12.5 ft) high. The long dimension of the compartment ran east-west. A 1.8 m (6 ft) wide, 2.4 m (8 ft) high door was centered on the east (short) wall. The compartment walls and ceiling were lined with 13 mm (0.5 in) thick gypsum board,[1] and the floor was covered with 13 mm (0.5 in) thick plywood covered by the same gypsum board panels that lined the walls and ceiling. An extra layer of 6 mm (0.25 in) thick cement board[2] was added to the walls and ceiling in the vicinity of the fire.

The fires were generated by four 30.5 cm (1 ft) square natural gas burners, ganged together and mounted on steel rails, 54 cm (21 in) above the floor. The steel rails allowed the burner to be pushed outward from the corner and wall during the experiments without being shut off. To ensure that the burner was initially tight against the wall and corner, a strip of mineral wool was inserted to seal the gap. The corner fire was located in the southwest corner of the large compartment. The wall fire was centered on the south (long) wall. The layout of the compartment is shown in Fig. 1.

The heat release rates (HRR) of the burner ranged from 200 kW to 400 kW. Internal calibrations at NIST indicate that the mass flow controller has an expan-

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[1] U.S. Gypsum Sheetrock brand gypsum panels. Estimated thermal properties from product literature are: specific heat, 1.1 kJ/(kg K), density, 700 kg/m^3, and thermal conductivity, 0.16 W/(m K).

[2] U.S. Gypsum Durock brand cement board. Estimated thermal properties from product literature are: specific heat, 1.0 kJ/(kg K), density, 925 kg/m^3, and thermal conductivity, 0.15 W/(m K).

Fig. 2. Photograph of the compartment showing the position of the wall (left) and corner (right) burners. The three-dimensional array of thermocouples is seen above the wall burner.

ded[3] relative uncertainty of approximately 1% for the range of flow rates required.

Four vertical thermocouple arrays spanning the height of the compartment were installed. One was located approximately 2 cm (1 in) from the southwest corner of the compartment where the corner fire experiments were conducted. A similar array was mounted halfway along the south wall where the wall fire experiments were conducted. Two arrays, located on the compartment centerline, were used to calculate the hot gas layer temperature and height using the method described in Ref. [9].

A three-dimensional array of thermocouples was mounted to rails attached to the ceiling above the burner (see Fig. 2). The array consisted of three 91 cm by 91 cm (36 in by 36 in) steel grids connected via vertical struts to a frame suspended below the ceiling. The thermocouple beads extended 5 cm (2 in) below the grid. The array travelled with the movable burner measuring maximum plume temperatures at heights of 2.12 m (6 ft, 11 in), 2.73 m (8 ft, 11 in), and 3.34 m (10 ft, 11 in) above the floor. For the corner and wall fire experiments, when the burner was at the 0 cm, 10 cm (4 in), and 20 cm (8 in) positions, the thermocouple array overhead remained at its original location in the corner or against the wall. As the burner moved beyond 20 cm (8 in), the thermocouple array was moved the same amount so that the burner was always below the array in the same position. In order to determine the peak plume temperature at each of the three levels, the individual TC temperatures were first time-averaged over a minute to eliminate spikes in the data, and then the maximum value of the averaged temperatures was chosen for each of the three levels.

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[3] 95% confidence interval.

3. Results

Experiments were conducted with fires of 200 kW, 300 kW, and 400 kW for both the wall and corner configuration. The gas flow was held steady for 2 h as the burner was moved from position to position. The burner was left on throughout the experiment to eliminate as much as possible transient heating of the walls in order to achieve a quasi-steady state plume. The experiments began with the quad burner in the corner or against the wall for the first 30 min. At 30 min, the burner was moved so that its edge(s) was 10 cm (4 in) away from the wall(s). It remained for 15 min, after which it was moved to 20 cm (8 in), 30 cm (12 in), 50 cm (20 in), 100 cm (40 in), and 160 cm (63 in), each time remaining 15 min for a total experiment time of 2 h.

The corner fire flame heights decreased noticeably after the opening of the initial 10 cm gap, as shown in Fig. 3. Subsequent shifts did not lead to noticeable changes in flame height, although the plume temperatures at the three measurement locations above the fire did continue to decrease. The wall fires exhibited no obvious change in flame height, nor a significant change in plume temperatures.

Figure 4 displays the plume temperatures at heights of 1.6 m (5 ft, 3 in), 2.2 m (7 ft, 3 in), and 2.9 m (9 ft, 6 in) above the top of the burner. It is obvious that the corner has a noticeable effect on the plume temperature as the burner is

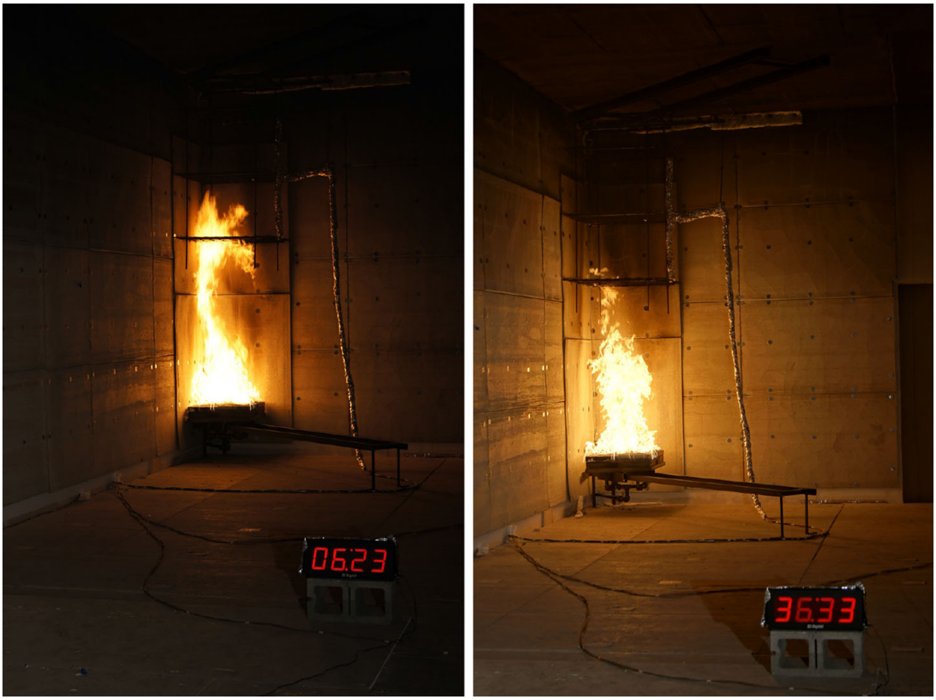

Fig. 3. Photographs of the 300 kW corner fire. At left, there is no gap between the pan and the corner; at right, there is a 10 cm gap.

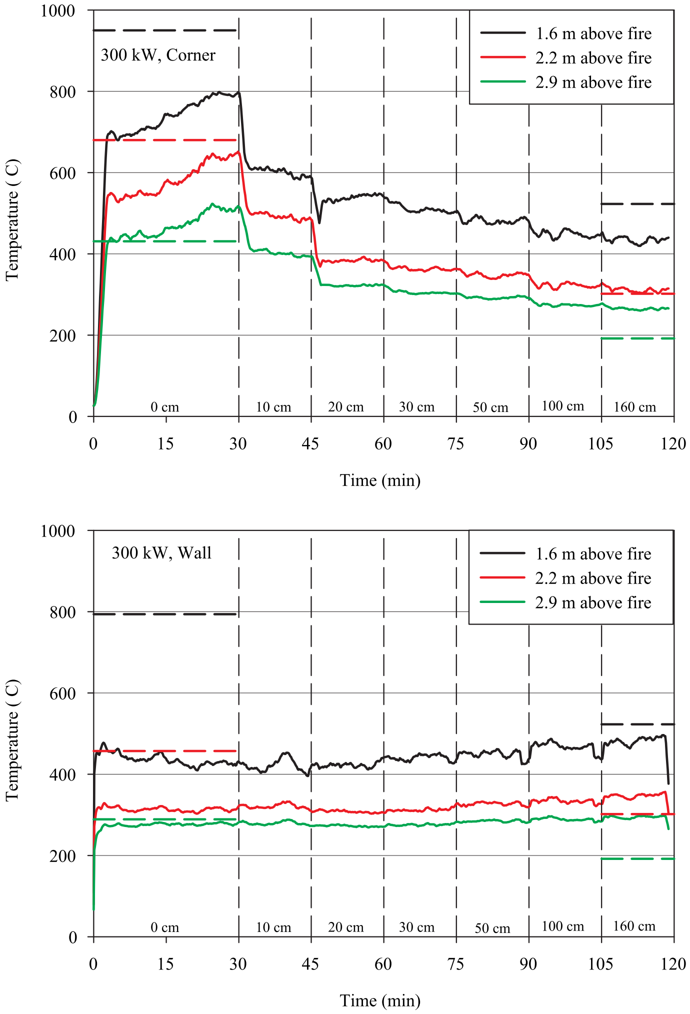

Fig. 4. Plume temperature at three heights above the 300 kW fires, for various distances from the corner (top) and wall (bottom). The horizontal dashed lines indicate the results of the Heskestad correlation, Eq. 1. The left set of lines uses a multiplicative factor of 4 for the corner and 2 for the wall, and the right set uses a factor of 1 for both.

moved away, but there is no such trend for the wall fire. The warming of the plume temperatures in the second hour of the wall fire experiments can be explained by the gradual heating of the compartment.

The horizontal, dashed lines on the plots in Fig. 4 covering the first 30 min and final 15 min of each experiment indicate temperatures calculated using Heskestad's plume correlation, Eq. (1). For the initial 30 min, when the fire is right up against the wall or corner, respectively, Eq. (1) is evaluated with two or four times the heat release rate and base area (i.e. D is multiplied by $\sqrt{2}$ and 2, respectively). For the final 15 min, Eq. (1) is evaluated using the actual heat release rate and fire base area. The base diameter, D, of the 0.6 m by 0.6 m (2 ft by 2 ft) square burner is taken as $D = \sqrt{4A/\pi} \approx 0.68$ m (2 ft, 3 in). In all cases, the radiative fraction of the fire is assumed to be 0.25; that is, the convective heat release rate, $\dot{Q}_c$, is assumed to be 75% of the total heat release rate [10]. No attempt has been made to account for the effect of the hot gas layer or ceiling when evaluating Heskestad's correlation, which can explain some of the differences with the actual measurements.

Figure 5 displays the HGL temperature and height for the 300 kW fires. There does not appear to be a significant change in either quantity as the burner is

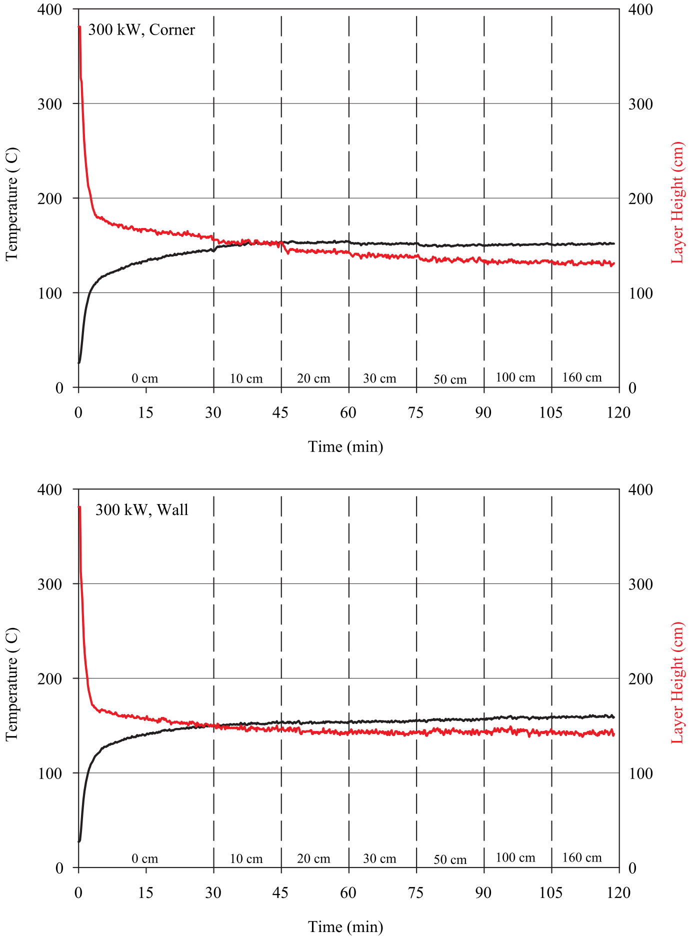

Fig. 5. HGL temperature (black) and height (red) for 300 kW corner (top) and wall (bottom) fires.

Table 1
Recommended Location Factor, k_F, for Wall and Corner Plume Analyses

Configuration	0–0.3 m (0–1 ft)	0.3–0.6 m (1–2 ft)	> 0.6 m [> 2 ft]
Corner	4	2	1
Wall	1	1	1

moved away from the corner or wall. The gradual increase in HGL temperature and decrease in HGL height are typical of any steady compartment fire. Similar results were obtained for the 200 kW and 400 kW experiments and can be found in the test report [8].

4. Conclusion

This paper describes a set of fire experiments that investigate the effects of walls and corners on a fire plume.

1. While the corner had a noticeable effect on the flame height and plume temperatures, the wall did not. The plume temperatures and visible flame heights did not appear to change as the fire moved away from the wall.
2. The hot gas layer temperature and height were not noticeably affected by the location of the fire. This might be the result of the relatively large compartment size—smaller compartments might demonstrate a more noticeable effect.

It is important to stress that these experiments were limited in scope. In particular, the fires were elevated off the floor, and when the burner was pulled away from the wall, air would be entrained from below, as well as from the side. It would be useful to redo these types of experiments with a burner positioned on the floor.

Based on these experiments and the accompanying CFD analysis, the NRC and EPRI modified the guidance for "location factor," k_F, as applied in Eq. (1). The new values are listed in Table 1. It is no longer assumed, for the purpose of hazard analyses, that the wall has an impact on the plume; whereas the original value of 4 is still applied when the fire is within 0.3 m of a corner. This new guidance is important because most potential fire sources in industrial facilities like nuclear power plants are not situated exactly against a wall or in a corner because access by plant personnel is required. The new guidance recognizes that the corner effect is most significant when the fire is literally abutting the corner, but its influence drops off fairly quickly as the gap between fire and corner increases.

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References

1. Heskestad G (2016) SFPE handbook of fire protection engineering, chapter fire plumes, flame height and air entrainment, 5th edn. Springer, New York
2. Zukoski EE, Kubota T, Cetegen B (1981) Entrainment in fire plumes. Fire Saf J 3:107–121
3. Lattimer BY, Sorathia U (2003) Thermal characteristics of fires in a noncombustible corner. Fire Saf J 38:709–745
4. Salley MH, Lindeman A (2020) Refining and characterizing heat release rates from electrical enclosures during fire, volume 2: fire modeling guidance for electrical cabinets, electric motors, indoor dry transformers, and the main control board. NUREG 2178, U.S. Nuclear Regulatory Commission, Washington, D.C., June 2020. Joint publication with the Electric Power Research Institute, EPRI 3002016052
5. Williamson RB, Revenaugh A, Mowrer FW (1991) Ignition sources in room fire tests and some implications for flame spread evaluation. In: fire safety science—proceedings of the third international symposium. International Association of Fire Safety Science, pp 657–666
6. Dembsey NA, Pagni PJ, Williamson B (1995) Compartment fire experiments: comparison with models. Fire Saf J 25:187–227
7. McGrattan K, Hostikka S, McDermott R, Floyd J, Weinschenk C, Overholt K (2013) Fire dynamics simulator, technical reference guide, volume 3: validation. National Institute of Standards and Technology, Gaithersburg, Maryland, USA, and VTT Technical Research Centre of Finland, Espoo, Finland, sixth edition, September 2013
8. McGrattan KB, Selepak MJ, Hnetkovsky EJ (2018) The influence of walls, corners and enclosures on fire plumes. NIST Technical Note 1984, National Institute of Standards and Technology. Gaithersburg, Maryland, March 2018
9. Janssens ML, Tran HC (1992) Data reduction of room tests for zone model validation. J Fire Sci 10:528–555
10. Beyler CL (2016) SFPE handbook of fire protection engineering, chapter fire hazard calculations for large open hydrocarbon fires, 5th edn. Springer, New York