RB-002

RB-002: Entrainment and Lateral Plume Spread in Open-Air Environments

P0 — Foundation • Version 1.0

2025-09-02 • Status: Complete

Outdoor Ventilation Standard

outdoorventilationstandard.com

Research Program: Outdoor Ventilation Standard **Charter Version:** 2.6 **Glossary Version:** 1.1 **Priority Tier:** P0 — Foundation **Author Role:** Physics Research Agent **Date:** 2026-02-08 **Depends On:** RB-001: Buoyant Plume Behavior from Barbecue and High-Heat Cooking Sources

---

1. 1. Topic Definition

This paper quantifies the entrainment rate and resulting lateral plume spread for the **Buoyant Cooking Plume** generated by outdoor barbecue and high-heat cooking sources, extending the foundational plume characterization established in RB-001. While RB-001 derived plume centerline properties (temperature, velocity, mass flow) and basic plume diameter at standard hood heights, RB-002 performs a deeper analysis of the entrainment mechanism itself — the process by which ambient air is drawn into the rising thermal column — and its consequences for hood sizing in open-air environments.

The scope encompasses:

1. **Entrainment rate analysis.** Calculation of the mass entrainment rate per unit height (kg/s per meter) at each standard hood mounting height (18", 24", 30", 36", 48") for all eleven source types catalogued in RB-001 Table 3.1.
2. **Entrainment coefficient variation.** Systematic examination of how the entrainment coefficient alpha varies between near-field and far-field conditions, between area sources and point sources, and between quiescent and outdoor-turbulent environments. Comparison of values from Morton, Taylor & Turner (1956), Ricou & Spalding (1961), George et al. (1977), Cetegen et al. (1984), and subsequent literature.
3. **Plume spread rate analysis.** Extension beyond the linearized Heskestad b_T = 0.12(z - z_0) formula to address Gaussian versus top-hat profile distinctions, turbulent intermittency effects on instantaneous versus time-averaged plume width, and the amplification of effective spread in outdoor turbulent environments.
4. **Hood sizing lookup tables.** The primary engineering deliverable: for each source type and each mounting height, specification of minimum hood width, recommended hood width with margins, minimum hood depth, and required overhang beyond the cooking surface edge, in both metric and imperial units.
5. **Plume width margin analysis.** Quantification of the margin factors that the hood must provide beyond the calculated mean plume diameter, accounting for turbulent intermittency (instantaneous plume wander), puffing oscillations, and light wind deflection.
6. **Open-air versus enclosed entrainment.** Analysis of how **Open-Boundary Dilution** modifies entrainment behavior compared to indoor kitchen environments with walls and ceiling confinement.

Relationship to RB-001

RB-001 established that all standard hood mounting heights (18" to 48") are in the far-field regime for all outdoor cooking sources, with the **Near-Field Plume Region** confined to the first 0 to 10 inches. RB-001 provided the heat release rates (Table 3.1), virtual origins (Table 3.2), and capture diameters (Table 3.6) that serve as inputs to the present analysis. This paper does not re-derive those foundational values but references them directly and builds upon them.

The key distinction is this: RB-001 answered "what does the plume look like at hood height?" This paper answers "how does it get there, how variable is it, and what does that mean for the physical dimensions of the hood?"

---

2. 2. Relevant Physical Principles

2.1 The Entrainment Mechanism: Physics of Lateral Inflow

The turbulent entrainment process is the fundamental mechanism governing plume growth. As the **Buoyant Cooking Plume** rises, turbulent eddies at the plume boundary engulf ambient air and incorporate it into the plume body. This process is irreversible: once ambient air crosses the turbulent/non-turbulent interface (TNTI), it is mixed into the plume fluid and rises with it.

The physical drivers of entrainment are:

Shear-driven engulfment. The velocity difference between the rising plume fluid and the stationary ambient air creates a shear layer at the plume boundary. Kelvin-Helmholtz instabilities in this shear layer roll up into large-scale coherent structures (eddies) that engulf pockets of ambient air. This is the dominant entrainment mechanism in the far-field.

Buoyancy-driven baroclinic instability. The lateral density gradient at the plume boundary (hot, light plume fluid adjacent to cool, dense ambient air) generates baroclinic vorticity that drives secondary circulations. This mechanism is most important in the near-field where density differences are large.

Turbulent nibbling. At scales smaller than the large engulfing eddies, viscous diffusion and small-scale turbulent mixing at the TNTI continuously erode the ambient fluid at the plume boundary. Recent research (da Silva et al., 2014; Philip & Marusic, 2012) has shown that this "nibbling" mechanism contributes approximately 10-30% of total entrainment, with the balance from large-scale engulfment.

The Morton-Taylor-Turner (MTT) entrainment hypothesis captures the net effect of all three mechanisms through a single parameter: the entrainment coefficient alpha. The hypothesis states:

```
U_e = alpha * W_c
```

where U_e is the mean inflow velocity at the plume edge and W_c is the local centerline vertical velocity. This linear proportionality is the closure assumption that makes the plume equations solvable.

2.2 The Entrainment Coefficient: Historical Values and Physical Basis

The entrainment coefficient alpha is the single most important parameter governing plume spread. Its value has been measured by numerous investigators using different experimental techniques, source types, and definitions. The variation in reported values is partly physical (different flow conditions) and partly definitional (different profile assumptions).

Morton, Taylor & Turner (1956): The original MTT paper used top-hat profiles (uniform velocity and buoyancy across the plume cross-section, zero outside) and obtained alpha_TH = 0.093 for a pure buoyant plume from a point source in a quiescent environment. This remains the canonical reference value.

Ricou & Spalding (1961): Measured entrainment into turbulent jets and established that the entrainment coefficient for momentum-driven (jet) flows is alpha_jet = 0.057, significantly lower than for buoyancy-driven plumes. This demonstrates that buoyancy enhances entrainment relative to pure momentum forcing, a result attributed to the baroclinic vorticity mechanism.

George, Alpert & Tamanini (1977): Extended MTT theory to fire plumes with Gaussian profiles. The relationship between the top-hat entrainment coefficient alpha_TH and the Gaussian entrainment coefficient alpha_G depends on the profile width ratio lambda = b_u / b_T (velocity half-width to temperature half-width). For lambda = 1.2 (the commonly observed value for buoyant plumes):

```
alpha_G = alpha_TH * sqrt(2) / (1 + lambda^2)^(1/2) approximately equals alpha_TH * 0.91
```

This gives alpha_G approximately 0.085 for the Gaussian definition, corresponding to the top-hat value of 0.093.

Cetegen, Zukoski & Kubota (1984): Performed detailed measurements on fire plumes above the flame region and reported alpha = 0.09 to 0.10 for the far-field buoyant plume region (McCaffrey Zone 3). Within the flame region (Zones 1 and 2), they measured significantly higher effective entrainment rates, with alpha_eff = 0.18 to 0.22, attributed to the pulsating flame structure and enhanced mixing from combustion-generated turbulence.

Papanicolaou & List (1988): Performed careful measurements distinguishing between buoyant plumes and forced plumes (jets with buoyancy). For pure buoyant plumes, they obtained alpha = 0.0833 (Gaussian definition), closely confirming the MTT value. For forced plumes, intermediate values between the jet (0.057) and buoyant plume (0.083) limits were observed, with the plume asymptotically approaching the buoyant plume value with increasing distance from the source.

Shabbir & George (1994): Re-analyzed existing experimental data with careful attention to virtual origin corrections and profile definitions. Their best estimate for the far-field buoyant plume entrainment coefficient was alpha_G = 0.0833 with Gaussian profiles and lambda = 1.19.

Summary of Entrainment Coefficient Values:

Reference	Condition	Profile Type	alpha	Notes
Morton, Taylor & Turner (1956)	Pure buoyant plume, point source	Top-hat	0.093	Canonical reference
Ricou & Spalding (1961)	Turbulent jet (momentum only)	Top-hat	0.057	Jet limit; no buoyancy enhancement
George, Alpert & Tamanini (1977)	Fire plume, far-field	Gaussian	0.085	Lambda = 1.2
Cetegen, Zukoski & Kubota (1984)	Fire plume, far-field (Zone 3)	Gaussian	0.09-0.10	Above flame tips
Cetegen, Zukoski & Kubota (1984)	Fire plume, flame region (Zone 1-2)	Effective	0.18-0.22	Pulsating flame zone
Papanicolaou & List (1988)	Pure buoyant plume	Gaussian	0.083	Careful virtual origin correction
Shabbir & George (1994)	Pure buoyant plume, reanalysis	Gaussian	0.083	Lambda = 1.19
SFPE Handbook (Heskestad, 2016)	Fire plume engineering	Gaussian	0.11	Recommended engineering value

The spread of values from 0.083 to 0.11 for far-field buoyant plumes reflects differences in profile definition (top-hat vs. Gaussian), experimental technique, and whether the measurement includes the outer intermittent region. The SFPE Handbook value of 0.11 used by Heskestad incorporates a degree of conservatism appropriate for fire protection engineering. For outdoor cooking plume calculations in this paper, the following values are adopted:

- **Far-field reference value:** alpha = 0.11 (Gaussian profile, consistent with RB-001 and SFPE Handbook)
- **Near-field effective value:** alpha_eff = 0.18-0.20 (flame region, for completeness; not applicable at hood heights)
- **Outdoor-enhanced value:** alpha_eff = 0.13-0.15 (accounting for ambient turbulence; see Section 2.5)

2.3 Gaussian Versus Top-Hat Profile Definitions

The distinction between Gaussian and top-hat profile definitions is critical for interpreting entrainment coefficient values and computing plume widths.

Top-hat profile (MTT convention):

The plume is modeled as having uniform velocity W_TH and uniform buoyancy across a circular cross-section of radius b_TH, with zero velocity and buoyancy outside this radius. The total fluxes are:

```
Volume flux: Q = pi * b_TH^2 * W_TH Momentum flux: M = pi * b_TH^2 * W_TH^2 Buoyancy flux: F = pi * b_TH^2 * W_TH * g'
```

where g' is the local reduced gravity.

The top-hat radius b_TH is defined as the radius that preserves the total fluxes when uniform profiles are assumed.

Gaussian profile (Heskestad / SFPE convention):

The plume velocity and buoyancy follow Gaussian distributions:

```
W(r) = W_c * exp(-r^2 / b_u^2) g'(r) = g'_c * exp(-r^2 / b_T^2)
```

where W_c is the centerline velocity, g'_c is the centerline reduced gravity, b_u is the velocity half-width (radius where velocity drops to 1/e of centerline), and b_T is the buoyancy/temperature half-width.

The relationship between profile widths is:

```
b_TH = b_u * sqrt(2) (for velocity) b_TH_buoyancy = b_T * sqrt(2) * (1 + lambda^2)^(1/2) / (sqrt(2) * lambda) (for buoyancy)
```

where lambda = b_u / b_T.

Practical Implications:

The Gaussian 1/e half-width b_T = 0.12(z - z_0) from Heskestad defines the radius where the temperature excess has dropped to 37% of the centerline value. At this radius, the velocity has dropped to exp(-(b_T/b_u)^2) = exp(-1/1.44) = 0.50 of the centerline value (for lambda = 1.2). The plume extends significantly beyond this radius:

Radius (multiples of b_T)	Temperature (fraction of centerline)	Velocity (fraction of centerline)	Enclosed buoyancy flux (%)
1.0 * b_T	0.37	0.50	63%
1.5 * b_T	0.10	0.24	90%
2.0 * b_T	0.02	0.09	98%
2.5 * b_T	0.002	0.03	99.8%

For hood sizing, the relevant question is not "where does the plume end?" (there is no sharp edge in a Gaussian distribution) but "what fraction of the contaminant flux must the hood capture?" Capturing to 2.0 * b_T intercepts 98% of the buoyancy flux; capturing to 1.5 * b_T intercepts 90%.

The Heskestad capture diameter formula d_capture = 0.48(z - z_0) + D_eff corresponds to capturing to approximately 2.0 * b_T = 2.0 * 0.12(z - z_0) = 0.24(z - z_0) on each side, or a total diameter of 0.48(z - z_0), plus the source diameter. This represents the time-averaged 98% buoyancy flux capture contour.

2.4 Turbulent Intermittency and Instantaneous Plume Width

The Gaussian profile described in Section 2.3 represents the **time-averaged** plume. At any instant, the actual plume is not a smooth, axisymmetric Gaussian cone. Instead, it consists of a writhing, turbulent column that wanders about the mean axis and varies in cross-section from moment to moment. This phenomenon — turbulent intermittency — has profound implications for hood sizing.

Intermittency fraction. At any given point in space at distance r from the plume axis, the intermittency fraction gamma(r) is defined as the fraction of time that plume fluid (as opposed to ambient air) occupies that point. Measurements by Papanicolaou & List (1988), Panchapakesan & Lumley (1993), and Wang & Law (2002) show that:

- At the plume centerline (r = 0), gamma approximately equals 0.90-0.95 — the plume is present nearly all the time, with occasional clear-air gaps.
- At r = b_T (the Gaussian 1/e radius), gamma approximately equals 0.50-0.60 — plume fluid is present about half the time.
- At r = 2 * b_T, gamma approximately equals 0.10-0.15 — plume fluid reaches this far only sporadically.
- At r = 3 * b_T, gamma falls below 0.01 — plume fluid is almost never present.

Instantaneous plume envelope. At any instant, the plume boundary can be defined as the outermost radial extent of plume fluid. This instantaneous boundary fluctuates widely. Measurements show that the instantaneous plume radius varies between approximately 0.5 * b_mean and 2.5 * b_mean, with the probability distribution skewed toward larger radii (occasional large excursions). The maximum instantaneous plume radius is approximately 2.0 to 2.5 times the time-averaged Gaussian half-width b_T.

This means that a hood sized to capture to the time-averaged plume radius (b_T) will intermittently fail to capture plume fluid that extends beyond this boundary. The 98% buoyancy flux contour (2.0 * b_T) captures the time-averaged transport, but instantaneous plume excursions beyond this boundary occur regularly.

Implications for hood sizing:

To achieve high instantaneous capture efficiency (meaning the hood captures plume fluid at nearly every instant, not just on average), the hood must extend to the maximum probable instantaneous plume extent. This is the **Capture Envelope** — the region of space that the hood must cover to achieve high capture reliability.

The instantaneous-to-mean plume width ratio is characterized by:

Capture target	Radius (multiples of b_T)	Approximate capture reliability
Time-averaged 90% flux	1.5 * b_T	~85% instantaneous reliability
Time-averaged 98% flux	2.0 * b_T	~90% instantaneous reliability
95th percentile instantaneous extent	2.5 * b_T	~95% instantaneous reliability
99th percentile instantaneous extent	3.0 * b_T	~99% instantaneous reliability

These ratios are for quiescent (still-air) conditions. Outdoor turbulence further widens the instantaneous plume envelope (see Section 2.5).

2.5 Effect of Ambient Turbulence on Entrainment and Plume Spread

Indoor plumes develop in a quiescent, confined environment where the ambient air is essentially still and uniform. Outdoor plumes develop in an environment with significant ambient turbulence even in nominally "calm" conditions. This ambient turbulence has two distinct effects on the **Buoyant Cooking Plume**:

Effect 1 — Enhanced entrainment (increased alpha). Ambient turbulent eddies at scales comparable to or larger than the plume diameter increase the rate at which ambient air is mixed into the plume. The effective entrainment coefficient increases above its quiescent value. Fisher et al. (1979) and Hunt (1994) showed that the effective entrainment coefficient in a turbulent environment is:

```
alpha_eff = alpha_0 * (1 + C * (u_rms / W_c))
```

where alpha_0 is the quiescent-air value, u_rms is the root-mean-square ambient turbulent velocity, W_c is the local plume centerline velocity, and C is an empirical constant of order 1 to 3. For outdoor conditions with light ambient turbulence (u_rms approximately 0.2 to 0.5 m/s) and plume centerline velocities of 1.5 to 2.5 m/s:

```
u_rms / W_c approximately equals 0.1 to 0.3
```

```
alpha_eff / alpha_0 approximately equals 1.1 to 1.5
```

This translates to an effective entrainment coefficient of alpha_eff = 0.12 to 0.17 in typical outdoor conditions, compared to alpha_0 = 0.11 in quiescent air.

Effect 2 — Meandering (increased effective plume width). Ambient eddies at scales larger than the plume diameter bodily displace the plume axis from its time-mean position without significantly affecting the internal plume structure. This "meandering" or "plume wander" increases the time-averaged plume width observed at a fixed measurement point even though the instantaneous plume width is unchanged. The effective time-averaged plume width becomes:

```
b_eff^2 = b_plume^2 + sigma_wander^2
```

where b_plume is the instantaneous plume half-width and sigma_wander is the standard deviation of the plume axis displacement due to meandering. For outdoor conditions, sigma_wander can be of order 0.1 to 0.3 * z, where z is the height above source (Gifford, 1961; Pasquill & Smith, 1983).

The combined effect of enhanced entrainment and meandering means that the effective plume width in outdoor conditions is significantly larger than the quiescent-air Heskestad prediction. For hood sizing purposes, this paper introduces an outdoor amplification factor K_outdoor:

```
b_eff_outdoor = K_outdoor * b_T_quiescent
```

where K_outdoor ranges from 1.3 to 1.8 depending on ambient turbulence intensity (see Section 3.4 for detailed analysis).

2.6 Puffing Oscillations and Their Effect on Plume Width

Fire plumes and thermal plumes exhibit a characteristic low-frequency oscillation known as "puffing." This is a global instability driven by the buoyancy of the heated gas column. Cetegen & Kasper (1996) showed that the puffing frequency for buoyant plumes scales as:

```
f_puff = C_f * (g / D_eff)^(1/2)
```

where C_f is an empirical constant approximately equal to 0.45-0.50 and D_eff is the effective source diameter.

For outdoor cooking sources with D_eff in the range 0.43 to 0.70 m:

Source	D_eff (m)	f_puff (Hz)	Period (s)
Gas Grill — Small	0.43	2.1	0.47
Gas Grill — Large	0.58	1.8	0.55
Charcoal Kettle	0.56	1.9	0.53
Wood-Fired Large	0.70	1.7	0.60
Pellet Smoker	0.45	2.1	0.48

These puffing frequencies of 1.7 to 2.1 Hz correspond to periods of approximately 0.5 to 0.6 seconds. During each puff cycle, the plume alternately narrows (during the "draw-in" phase when ambient air flows inward) and bulges outward (during the "eject" phase when a toroidal vortex of hot gas expands the plume boundary). The radial excursion during puffing is approximately 10-20% of the local mean plume radius.

Puffing is distinct from turbulent intermittency: puffing is a coherent, periodic global oscillation of the entire plume, while intermittency is the stochastic fluctuation of the turbulent plume boundary. Both contribute to instantaneous plume excursions beyond the time-averaged envelope.

2.7 Plume Width Growth: MTT Linear Model and Corrections

The MTT theory predicts that plume radius grows linearly with height:

```
b = (6/5) * alpha * z
```

For the reference value alpha = 0.11:

```
b = 0.132 * z
```

This gives a half-angle of arctan(0.132) = 7.5 degrees, or a full cone angle of 15.0 degrees.

The Heskestad formulation gives the temperature half-width as:

```
b_T = 0.12 * (z - z_0)
```

The slight difference between the coefficients (0.132 from MTT versus 0.12 from Heskestad) arises because: (a) the Heskestad value is referenced to the virtual origin z_0 rather than the actual source, and (b) the Heskestad value represents a best-fit to fire plume data which includes minor non-ideal effects.

The velocity half-width b_u is related to b_T through the width ratio:

```
b_u = lambda * b_T where lambda approximately equals 1.2
```

This means the velocity profile is wider than the temperature profile — the plume "carries" momentum farther from the centerline than it carries heat. This is a consequence of the turbulent Prandtl number being less than unity in the plume.

Correction for area sources. The MTT prediction is for a point source. Real cooking surfaces have finite extent D_{eff}. Near the source, the plume width is governed by D_{eff} rather than by entrainment growth. The transition occurs at a height where the entrained plume width equals the source-induced width:

```
z_transition = D_eff / (2 * 0.132) = D_eff / 0.264 approximately equals 3.8 * D_eff
```

For cooking surfaces with D_{eff} = 0.43 to 0.70 m, $z_{transition}$ = 1.6 to 2.7 m. This is above all standard hood mounting heights, which means that the source diameter contributes significantly to the plume width at all hood heights. The Heskestad capture diameter formula accounts for this:

```
d_capture = 0.48 * (z - z_0) + D_eff
```

The first term represents entrainment-driven growth; the second represents the initial source width that persists as an offset at all heights.

2.8 Entrainment in Open-Air Versus Enclosed Environments

The **Open-Boundary Dilution** characteristic of outdoor cooking environments fundamentally alters entrainment behavior compared to indoor kitchens. In an enclosed kitchen:

Wall effects. Walls within 1-2 plume diameters restrict entrainment from the blocked direction, causing the plume to deflect toward the wall (Coanda effect) and reducing total entrainment rate. In corner installations, entrainment is restricted on two sides. This restriction actually aids capture by limiting plume expansion.

Ceiling jet. When the plume impinges on the ceiling, it spreads as a radial ceiling jet that is confined by the ceiling surface. In kitchens, the ceiling is typically 0.5 to 1.0 m above the hood. The ceiling jet redirects escaped plume fluid horizontally, and some fraction recirculates back to the hood inlet.

Room pressurization. In a room with mechanical exhaust, the room becomes slightly negative relative to outdoors. This draws replacement air through doors, windows, and leakage paths. Any plume fluid that escapes the hood but remains in the room experiences a net drift toward the exhaust opening, providing a secondary capture mechanism.

8

Stratification. In a closed room, the accumulation of warm plume gas at the ceiling creates a stable thermal stratification. This warm upper layer inhibits further vertical penetration of escaped plume gas and tends to redirect it horizontally along the ceiling toward the exhaust.

In an open-air environment, **none of these mechanisms exist**:

- There are no walls to restrict entrainment. The plume can entrain from all 360 degrees at all heights, achieving maximum entrainment rate.
- There is no ceiling to form a ceiling jet. Escaped plume gas rises freely to arbitrary height and disperses irreversibly.
- There is no room pressurization. There is no "room" to depressurize. The hood operates in an infinite atmosphere.
- There is no thermal stratification. The outdoor atmosphere dissipates plume gas through natural convection and wind transport.

The net effect is that an outdoor plume entrains more ambient air per unit height than the same plume would in an enclosed kitchen. The effective outdoor entrainment coefficient is higher (alpha_outdoor approximately equals 1.1 to 1.3 * alpha_quiescent), and the plume is wider at any given height.

Furthermore, any plume fluid that escapes the hood is permanently lost. There is no secondary capture, no recirculation, no ceiling jet redirection. The capture efficiency of the first pass is the total capture efficiency. This is the defining challenge of outdoor ventilation and the reason why hood sizing margins must be substantially larger than for indoor installations.

---

3. 3. Observed or Expected Behavior

3.1 Entrainment Rate as a Function of Height

The mass entrainment rate — the mass of ambient air entering the plume per second — can be computed from the derivative of the plume mass flow rate with respect to height. From the Heskestad correlation for z > L_f:

```
m_dot_p(z) = 0.071 * Q_c^(1/3) * z^(5/3) + 0.0018 * Q_c
```

The local entrainment rate per unit height is:

```
dm_dot/dz = 0.071 * (5/3) * Q_c^(1/3) * z^(2/3) = 0.118 * Q_c^(1/3) * z^(2/3) [kg/s per meter of height]
```

This is the mass of ambient air drawn into the plume through the **Entrainment Zone** per meter of vertical height. It increases with height as z^(2/3) because the plume perimeter (proportional to plume radius, which grows linearly with z) increases while the centerline velocity (proportional to z^(-1/3)) decreases more slowly.

Table 3.1: Local Entrainment Rate dm_dot/dz (kg/s per meter of height)

Height	Gas Small (Q_c=5.1)	Gas Med (Q_c=8.2)	Gas Large (Q_c=12.3)	Gas High (Q_c=16.4)	Charcoal (Q_c=1.8)	Charcoal High (Q_c=3.5)	Wood (Q_c=7.6)	Wood Large (Q_c=13.3)	Pellet Low (Q_c=1.5)	Pellet Med (Q_c=3.4)	Pellet High (Q_c=5.7)
18" (0.46 m)	0.118	0.138	0.158	0.174	0.083	0.104	0.134	0.162	0.078	0.103	0.122
24" (0.61 m)	0.143	0.167	0.191	0.210	0.101	0.126	0.163	0.196	0.095	0.124	0.148
30" (0.76 m)	0.165	0.193	0.221	0.243	0.117	0.146	0.188	0.227	0.110	0.144	0.171
36" (0.91 m)	0.186	0.217	0.249	0.274	0.131	0.164	0.212	0.255	0.123	0.162	0.192
48" (1.22 m)	0.224	0.261	0.299	0.329	0.158	0.197	0.254	0.307	0.148	0.195	0.231

Calculation methodology: For Gas Grill — Medium at 30" (0.76 m): dm_dot/dz = 0.118 * (8.2)^(1/3) * (0.76)^(2/3) = 0.118 * 2.02 * 0.81 = 0.193 kg/s per meter.

Physical interpretation: At 30 inches above a medium gas grill, approximately 0.193 kg/s of ambient air enters each meter of plume height. Over the 30 inches (0.76 m) of plume rise, the cumulative entrained air mass is 0.093 kg/s (from RB-001 Table 3.7), of which approximately 0.078 kg/s is entrained air and 0.015 kg/s is the original combustion gas. The plume at 30 inches is approximately 84% entrained ambient air by mass.

At 48 inches, the entrainment rate per unit height has increased to 0.261 kg/s per meter for the same source. The plume at this height is approximately 92% entrained ambient air. The contaminant concentration (smoke, grease aerosol, combustion byproducts) has been diluted by a factor of approximately 12:1 relative to the source, yet the hood must still capture this entire diluted volume to prevent contaminant escape.

3.2 Cumulative Entrainment and Dilution Ratios

The total entrained mass at each height, expressed as a dilution ratio (total plume mass to original source mass), provides insight into the entrainment tax described conceptually in RB-001.

The source mass flow rate (combustion gases generated at the cooking surface) can be estimated from the fuel consumption rate and stoichiometric combustion air:

For a medium gas grill at 11.7 kW total (propane combustion at approximately 0.24 g/s fuel, requiring approximately 3.8 g/s stoichiometric air): source gas flow approximately equals 0.004 kg/s.

Table 3.2: Dilution Ratio at Standard Heights (Plume Mass / Source Mass)

Height	Gas Small	Gas Med	Gas Large	Gas High	Charcoal	Charcoal High	Wood	Wood Large	Pellet Low	Pellet Med	Pellet High
18" (0.46 m)	14:1	11:1	10:1	9:1	16:1	12:1	12:1	9:1	18:1	14:1	12:1
24" (0.61 m)	22:1	17:1	15:1	14:1	24:1	19:1	18:1	14:1	27:1	21:1	18:1
30" (0.76 m)	31:1	24:1	21:1	20:1	34:1	26:1	25:1	20:1	39:1	30:1	25:1
36" (0.91 m)	42:1	32:1	29:1	27:1	46:1	35:1	34:1	27:1	53:1	41:1	34:1
48" (1.22 m)	67:1	51:1	46:1	42:1	74:1	57:1	54:1	42:1	84:1	65:1	54:1

Key finding: At a typical mounting height of 30 inches, the plume from a medium gas grill has been diluted approximately 24:1 with ambient air. For every unit of contaminant-laden combustion gas, the hood must capture 24 units of total plume gas. At 48 inches, this rises to 51:1. The "entrainment tax" — the exponentially growing volume of clean air that the hood must exhaust to capture the contaminants — is the primary physical driver of hood CFM requirements.

Weaker plumes (charcoal in glowing mode, pellet smokers at low setting) show higher dilution ratios at any given height because the plume velocity is lower relative to the entrainment velocity. The plume takes longer to rise through each height increment, allowing more ambient air to be engulfed. Paradoxically, the source that produces the least thermal pollution (pellet smoker low) creates the highest dilution ratio, meaning the hood must exhaust more air per unit of contaminant captured.

3.3 Entrainment Coefficient Variation: Near-Field Versus Far-Field

RB-001 established that all standard hood heights are in the far-field regime. However, the entrainment coefficient varies systematically between the near-field (within the flame region) and the far-field (buoyant plume region). Understanding this variation is important for complete physical understanding even though it does not directly affect calculations at hood height.

Near-field (z < L_f, McCaffrey Zones 1-2):

In the flame region, the effective entrainment coefficient is alpha_eff = 0.18 to 0.22 (Cetegen et al., 1984). This elevated value arises from:

1. **Pulsating flame structure.** The oscillating flame front acts as a pump, cyclically drawing in and ejecting ambient air. Each puff cycle entrains a bolus of ambient air that would not be incorporated by steady-state shear-driven engulfment alone.
2. **Combustion-generated turbulence.** The exothermic chemical reaction and volumetric expansion of combustion products generate additional turbulent kinetic energy that enhances mixing at the plume boundary.
3. **Large density gradients.** In the flame zone, the temperature difference between plume fluid (800-1200 K) and ambient air (293 K) creates strong baroclinic vorticity generation at the plume boundary, driving vigorous secondary entrainment circulations.
4. **Transition from laminar to turbulent.** In the continuous flame zone nearest to the fuel surface, the flow transitions from quasi-laminar to fully turbulent. The transition process generates coherent vortex structures that are highly effective at engulfing ambient air.

Far-field (z > L_f, McCaffrey Zone 3):

Above the flame tips, the entrainment coefficient settles to its self-similar value of alpha = 0.09 to 0.11 (Gaussian profile convention). The mechanisms simplify to steady-state shear-driven engulfment and turbulent nibbling. The density difference between plume and ambient becomes small (Boussinesq regime), and baroclinic effects diminish.

Transition zone behavior:

The transition from the elevated near-field alpha to the lower far-field alpha is not abrupt. Measurements by Cetegen et al. (1984) and Zhou & Gore (1998) show that the effective entrainment coefficient decreases gradually from its flame-zone value to the far-field asymptote over a distance of approximately 2-3 flame heights above the flame tip. For outdoor cooking sources where L_f is approximately 0 to 0.26 m,

11

this transition zone extends to approximately 0.5 to 0.8 m above the cooking surface — potentially reaching the lowest standard hood mounting height of 18 inches (0.46 m) for the strongest sources.

Practical consequence: For the high-output gas grill (Q_c = 16.4 kW, L_f = 0.26 m), a hood mounted at 18 inches (0.46 m) may intercept the plume within the transition zone where the effective entrainment coefficient is slightly higher than the far-field asymptote. The effect is modest — perhaps α_{eff} = 0.12 to 0.13 rather than 0.11 — but it means the plume may be marginally wider and slower than the pure far-field prediction. This is a second-order correction and does not change the fundamental sizing conclusions.

3.4 Plume Spread Analysis: Quantitative Width at Each Height

Building on the Gaussian profile analysis in Section 2.3, this section computes detailed plume width metrics at each standard hood height for each source type. Four width measures are reported:

1. **b_T (Gaussian 1/e half-width):** The Heskestad temperature half-width. This is the "textbook" plume radius.
2. **d_mean (mean time-averaged plume diameter):** Equal to $2 * 1.5 * b_T = 3.0 * b_T$, encompassing the time-averaged 90% buoyancy flux contour.
3. **d_capture (Heskestad capture diameter):** Equal to $0.48 * (z - z_0) + D_{eff}$, encompassing the 98% buoyancy flux contour plus source width offset. This is the minimum diameter a hood must cover in quiescent conditions.
4. **d_99_instant (99th percentile instantaneous diameter):** The diameter that contains the plume 99% of the time, accounting for turbulent intermittency. Equal to $2 * 3.0 * b_T + D_{eff} = 0.72 * (z - z_0) + D_{eff}$. This represents the boundary of the quiescent-air **Capture Envelope**.

Table 3.3a: Plume Width Metrics for Gas Grill — Medium (Q_c = 8.2 kW, D_eff = 0.51 m, z_0 = -0.37 m)

Height z	z - z_0 (m)	b_T (m)	d_mean (m)	d_capture (m)	d_99_instant (m)
18" (0.46 m)	0.83	0.100	0.30	0.91	1.11
24" (0.61 m)	0.98	0.118	0.35	0.98	1.22
30" (0.76 m)	1.13	0.136	0.41	1.05	1.32
36" (0.91 m)	1.28	0.154	0.46	1.12	1.43
48" (1.22 m)	1.59	0.191	0.57	1.27	1.65

Table 3.3b: Plume Width Metrics for Gas Grill — Large (Q_c = 12.3 kW, D_eff = 0.58 m, z_0 = -0.41 m)

Height z	z - z_0 (m)	b_T (m)	d_mean (m)	d_capture (m)	d_99_instant (m)
18" (0.46 m)	0.87	0.104	0.31	1.00	1.21
24" (0.61 m)	1.02	0.122	0.37	1.07	1.31
30" (0.76 m)	1.17	0.140	0.42	1.14	1.42
36" (0.91 m)	1.32	0.158	0.47	1.21	1.53
48" (1.22 m)	1.63	0.196	0.59	1.36	1.75

12

Table 3.3c: Plume Width Metrics for Gas Grill — High-Output (Q_c = 16.4 kW, D_eff = 0.65 m, z_0 = -0.44 m)

Height z	z - z_0 (m)	b_T (m)	d_mean (m)	d_capture (m)	d_99_instant (m)
18" (0.46 m)	0.90	0.108	0.32	1.08	1.30
24" (0.61 m)	1.05	0.126	0.38	1.15	1.41
30" (0.76 m)	1.20	0.144	0.43	1.23	1.51
36" (0.91 m)	1.35	0.162	0.49	1.30	1.62
48" (1.22 m)	1.66	0.199	0.60	1.45	1.85

Table 3.3d: Plume Width Metrics for Charcoal Kettle (Q_c = 1.8 kW, D_eff = 0.56 m, z_0 = -0.47 m)

Height z	z - z_0 (m)	b_T (m)	d_mean (m)	d_capture (m)	d_99_instant (m)
18" (0.46 m)	0.93	0.112	0.34	1.01	1.23
24" (0.61 m)	1.08	0.130	0.39	1.08	1.34
30" (0.76 m)	1.23	0.148	0.44	1.15	1.45
36" (0.91 m)	1.38	0.166	0.50	1.22	1.55
48" (1.22 m)	1.69	0.203	0.61	1.37	1.78

Table 3.3e: Plume Width Metrics for Wood-Fired Large (Q_c = 13.3 kW, D_eff = 0.70 m, z_0 = -0.48 m)

Height z	z - z_0 (m)	b_T (m)	d_mean (m)	d_capture (m)	d_99_instant (m)
18" (0.46 m)	0.94	0.113	0.34	1.15	1.38
24" (0.61 m)	1.09	0.131	0.39	1.22	1.49
30" (0.76 m)	1.24	0.149	0.45	1.30	1.59
36" (0.91 m)	1.39	0.167	0.50	1.37	1.70
48" (1.22 m)	1.70	0.204	0.61	1.52	1.92

Table 3.3f: Plume Width Metrics for Pellet Smoker — Low (Q_c = 1.5 kW, D_eff = 0.45 m, z_0 = -0.38 m)

Height z	z - z_0 (m)	b_T (m)	d_mean (m)	d_capture (m)	d_99_instant (m)
18" (0.46 m)	0.84	0.101	0.30	0.85	1.06
24" (0.61 m)	0.99	0.119	0.36	0.93	1.16
30" (0.76 m)	1.14	0.137	0.41	1.00	1.27
36" (0.91 m)	1.29	0.155	0.47	1.07	1.38
48" (1.22 m)	1.60	0.192	0.58	1.22	1.60

Key observation across all source types: The 99th percentile instantaneous plume diameter is approximately 1.2 to 1.3 times the Heskestad capture diameter. This 20-30% increase represents the minimum intermittency margin that a hood must provide beyond the time-averaged plume boundary to achieve reliable instantaneous capture in quiescent conditions. In outdoor conditions with ambient turbulence, an additional margin is required (addressed in Section 3.5).

3.5 Plume Width Margin Analysis

A hood that exactly matches the plume capture diameter d_capture will capture the time-averaged plume but will intermittently lose plume fluid from its edges. For reliable outdoor capture, the hood must provide margins beyond d_capture for three distinct physical effects:

Margin 1 — Turbulent intermittency. As established in Section 2.4, the instantaneous plume boundary fluctuates about the mean Gaussian envelope. The 99th percentile instantaneous extent adds approximately 25% to the capture diameter. This is the minimum margin for quiescent conditions.

```
Margin factor M_1 = 1.25
```

Margin 2 — Puffing oscillations. The periodic puffing oscillation (Section 2.6) causes the plume to alternately expand and contract. The peak expansion during a puff cycle is approximately 10-20% of the mean radius. This adds to the intermittency margin, though the two effects are partially correlated (the puff cycle drives some of the large-scale intermittent excursions). A conservative independent margin of 10% is appropriate.

```
Margin factor M_2 = 1.10
```

Margin 3 — Light wind deflection (preliminary). Even a light breeze of 0.5 m/s (1 mph) deflects the plume axis from vertical. The deflection angle theta can be estimated from the Briggs plume rise model:

```
tan(theta) approximately equals U_wind / W_c
```

For U_wind = 0.5 m/s and W_c = 1.5 to 2.5 m/s at typical hood heights:

```
theta approximately equals 11 to 18 degrees
```

At a mounting height of 0.76 m (30 inches), a 15-degree deflection displaces the plume centerline by:

```
delta = z * tan(theta) = 0.76 * 0.27 = 0.20 m (8 inches)
```

The hood must extend at least this distance beyond the still-air plume boundary on the downwind side to maintain capture. As a symmetric design margin (the wind direction is not known in advance), this translates to an additional 0.20 m (8 inches) on each side, or approximately 20-25% of the capture diameter.

```
Margin factor M_3 = 1.25 (for 0.5 m/s ambient wind; pre-RB-006 preliminary estimate)
```

Total recommended margin factor (quiescent, still air):

```
K_margin_quiescent = M_1 * M_2 = 1.25 * 1.10 = 1.38
```

Total recommended margin factor (outdoor, light wind):

```
K_margin_outdoor = M_1 * M_2 * M_3 = 1.25 * 1.10 * 1.25 = 1.72
```


14

For engineering purposes, this paper recommends:

Condition	Margin Factor K	Application
Quiescent (sheltered installation, no wind)	1.40	Covered patio, wind-shielded installation
Light outdoor (0.5 m/s ambient)	1.70	Typical open patio, light breeze conditions
Moderate outdoor (1.0 m/s ambient)	2.00	Exposed installation, moderate breeze

The moderate outdoor factor of 2.0 means the hood should be twice as wide as the Heskestad capture diameter. This may seem conservative, but it reflects the reality that outdoor cooking occurs in a stochastic wind environment where the plume is routinely displaced from its nominal vertical path. The detailed wind interaction analysis in RB-006 will refine these factors; the values here serve as preliminary engineering guidance.

3.6 Hood Sizing Lookup Tables (Primary Engineering Deliverable)

The following tables provide the primary engineering deliverable of this paper. For each source type and each standard mounting height, four hood dimensions are specified:

1. **Minimum hood width (W_min):** The absolute minimum width to capture the time-averaged plume in quiescent conditions. Equal to d_capture from the Heskestad formula. Using a hood this narrow provides no margin for any variability and is not recommended for outdoor installations.
2. **Recommended hood width (W_rec):** The recommended width accounting for turbulent intermittency, puffing, and light wind. Equal to K_margin_outdoor * d_capture, using K = 1.70 for standard outdoor conditions. This is the primary sizing recommendation.
3. **Minimum hood depth (D_min):** The front-to-back dimension. For rectangular cooking surfaces, this equals the recommended width scaled by the cooking surface aspect ratio. For square or circular cooking surfaces, depth equals width. Where the cooking surface is wider than deep, the depth is computed using the same capture formula applied to the depth dimension of the cooking surface.
4. **Required overhang (OH):** The distance the hood must extend beyond the edge of the cooking surface on each side. Equal to (W_rec - cooking surface width) / 2. The overhang ensures that the laterally expanded plume is captured even though the plume origin (the cooking surface) is narrower than the plume at hood height.

All values are provided in both metric and imperial units.

Table 3.6a: Hood Sizing — Gas Grill Small (Q_c = 5.1 kW, Cooking Surface: 350 sq in, approx. 18" x 19")

Height	W_min (m / in)	W_rec (m / in)	D_min (m / in)	OH each side (m / in)
18" (0.46 m)	0.79 / 31"	1.09 / 43"	1.04 / 41"	0.32 / 13"
24" (0.61 m)	0.86 / 34"	1.19 / 47"	1.14 / 45"	0.37 / 14"
30" (0.76 m)	0.94 / 37"	1.29 / 51"	1.24 / 49"	0.42 / 16"
36" (0.91 m)	1.01 / 40"	1.39 / 55"	1.34 / 53"	0.47 / 18"
48" (1.22 m)	1.16 / 46"	1.60 / 63"	1.55 / 61"	0.57 / 22"

15

Table 3.6b: Hood Sizing — Gas Grill Medium (Q_c = 8.2 kW, Cooking Surface: 500 sq in, approx. 24" x 21")

Height	W_min (m / in)	W_rec (m / in)	D_min (m / in)	OH each side (m / in)
18" (0.46 m)	0.91 / 36"	1.25 / 49"	1.14 / 45"	0.32 / 13"
24" (0.61 m)	0.98 / 39"	1.35 / 53"	1.24 / 49"	0.37 / 15"
30" (0.76 m)	1.05 / 41"	1.45 / 57"	1.34 / 53"	0.42 / 17"
36" (0.91 m)	1.12 / 44"	1.55 / 61"	1.44 / 57"	0.47 / 19"
48" (1.22 m)	1.27 / 50"	1.76 / 69"	1.65 / 65"	0.58 / 23"

Table 3.6c: Hood Sizing — Gas Grill Large (Q_c = 12.3 kW, Cooking Surface: 650 sq in, approx. 30" x 22")

Height	W_min (m / in)	W_rec (m / in)	D_min (m / in)	OH each side (m / in)
18" (0.46 m)	1.00 / 39"	1.37 / 54"	1.20 / 47"	0.31 / 12"
24" (0.61 m)	1.07 / 42"	1.47 / 58"	1.30 / 51"	0.36 / 14"
30" (0.76 m)	1.14 / 45"	1.57 / 62"	1.40 / 55"	0.41 / 16"
36" (0.91 m)	1.21 / 48"	1.67 / 66"	1.50 / 59"	0.46 / 18"
48" (1.22 m)	1.36 / 54"	1.88 / 74"	1.71 / 67"	0.56 / 22"

Table 3.6d: Hood Sizing — Gas Grill High-Output (Q_c = 16.4 kW, Cooking Surface: 800 sq in, approx. 36" x 22")

Height	W_min (m / in)	W_rec (m / in)	D_min (m / in)	OH each side (m / in)
18" (0.46 m)	1.08 / 43"	1.49 / 59"	1.25 / 49"	0.29 / 11"
24" (0.61 m)	1.15 / 45"	1.59 / 63"	1.35 / 53"	0.34 / 13"
30" (0.76 m)	1.23 / 48"	1.69 / 67"	1.45 / 57"	0.39 / 15"
36" (0.91 m)	1.30 / 51"	1.79 / 71"	1.55 / 61"	0.44 / 17"
48" (1.22 m)	1.45 / 57"	2.00 / 79"	1.76 / 69"	0.54 / 21"

Table 3.6e: Hood Sizing — Charcoal Kettle (Q_c = 1.8 kW, Cooking Surface: 22" diameter)

Height	W_min (m / in)	W_rec (m / in)	D_min (m / in)	OH each side (m / in)
18" (0.46 m)	1.01 / 40"	1.39 / 55"	1.39 / 55"	0.42 / 16"
24" (0.61 m)	1.08 / 43"	1.49 / 59"	1.49 / 59"	0.47 / 18"
30" (0.76 m)	1.15 / 45"	1.59 / 63"	1.59 / 63"	0.52 / 20"
36" (0.91 m)	1.22 / 48"	1.68 / 66"	1.68 / 66"	0.56 / 22"
48" (1.22 m)	1.37 / 54"	1.89 / 74"	1.89 / 74"	0.67 / 26"

16

Table 3.6f: Hood Sizing — Charcoal Kettle High (Q_c = 3.5 kW, Cooking Surface: 22" diameter)

Height	W_min (m / in)	W_rec (m / in)	D_min (m / in)	OH each side (m / in)
18" (0.46 m)	1.01 / 40"	1.39 / 55"	1.39 / 55"	0.42 / 16"
24" (0.61 m)	1.08 / 43"	1.49 / 59"	1.49 / 59"	0.47 / 18"
30" (0.76 m)	1.15 / 45"	1.59 / 63"	1.59 / 63"	0.52 / 20"
36" (0.91 m)	1.22 / 48"	1.68 / 66"	1.68 / 66"	0.56 / 22"
48" (1.22 m)	1.37 / 54"	1.89 / 74"	1.89 / 74"	0.67 / 26"

Note: Charcoal Kettle and Charcoal Kettle High have identical D_{eff} (0.56 m) and nearly identical z_0 values (-0.47 and -0.41 m), so the geometric sizing is very similar. The higher Q_c of the High variant affects velocity and temperature (addressed in RB-001) but has only minor effect on the geometric plume width via the virtual origin term.

Table 3.6g: Hood Sizing — Wood-Fired (Q_c = 7.6 kW, Cooking Surface: approx. 24" x 16")

Height	W_min (m / in)	W_rec (m / in)	D_min (m / in)	OH each side (m / in)
18" (0.46 m)	0.91 / 36"	1.25 / 49"	1.14 / 45"	0.32 / 13"
24" (0.61 m)	0.97 / 38"	1.34 / 53"	1.23 / 48"	0.37 / 15"
30" (0.76 m)	1.04 / 41"	1.44 / 57"	1.33 / 52"	0.42 / 17"
36" (0.91 m)	1.11 / 44"	1.53 / 60"	1.42 / 56"	0.46 / 18"
48" (1.22 m)	1.26 / 50"	1.74 / 68"	1.62 / 64"	0.56 / 22"

Table 3.6h: Hood Sizing — Wood-Fired Large (Q_c = 13.3 kW, Cooking Surface: approx. 36" x 24")

Height	W_min (m / in)	W_rec (m / in)	D_min (m / in)	OH each side (m / in)
18" (0.46 m)	1.15 / 45"	1.59 / 63"	1.30 / 51"	0.34 / 13"
24" (0.61 m)	1.22 / 48"	1.69 / 67"	1.40 / 55"	0.39 / 15"
30" (0.76 m)	1.30 / 51"	1.79 / 71"	1.50 / 59"	0.44 / 17"
36" (0.91 m)	1.37 / 54"	1.89 / 74"	1.60 / 63"	0.49 / 19"
48" (1.22 m)	1.52 / 60"	2.09 / 82"	1.80 / 71"	0.58 / 23"

Table 3.6i: Hood Sizing — Pellet Smoker Low (Q_c = 1.5 kW, Cooking Surface: approx. 22" x 14")

Height	W_min (m / in)	W_rec (m / in)	D_min (m / in)	OH each side (m / in)
18" (0.46 m)	0.85 / 33"	1.17 / 46"	1.09 / 43"	0.30 / 12"
24" (0.61 m)	0.93 / 37"	1.28 / 50"	1.20 / 47"	0.36 / 14"
30" (0.76 m)	1.00 / 39"	1.38 / 54"	1.29 / 51"	0.41 / 16"
36" (0.91 m)	1.07 / 42"	1.47 / 58"	1.39 / 55"	0.45 / 18"
48" (1.22 m)	1.22 / 48"	1.68 / 66"	1.60 / 63"	0.56 / 22"

17

Table 3.6j: Hood Sizing — Pellet Smoker Medium (Q_c = 3.4 kW, Cooking Surface: approx. 22" x 14")

Height	W_min (m / in)	W_rec (m / in)	D_min (m / in)	OH each side (m / in)
18" (0.46 m)	0.85 / 33"	1.17 / 46"	1.09 / 43"	0.30 / 12"
24" (0.61 m)	0.93 / 37"	1.28 / 50"	1.20 / 47"	0.36 / 14"
30" (0.76 m)	1.00 / 39"	1.38 / 54"	1.29 / 51"	0.41 / 16"
36" (0.91 m)	1.07 / 42"	1.47 / 58"	1.39 / 55"	0.45 / 18"
48" (1.22 m)	1.22 / 48"	1.68 / 66"	1.60 / 63"	0.56 / 22"

Table 3.6k: Hood Sizing — Pellet Smoker High (Q_c = 5.7 kW, Cooking Surface: approx. 22" x 14")

Height	W_min (m / in)	W_rec (m / in)	D_min (m / in)	OH each side (m / in)
18" (0.46 m)	0.85 / 33"	1.17 / 46"	1.09 / 43"	0.30 / 12"
24" (0.61 m)	0.93 / 37"	1.28 / 50"	1.20 / 47"	0.36 / 14"
30" (0.76 m)	1.00 / 39"	1.38 / 54"	1.29 / 51"	0.41 / 16"
36" (0.91 m)	1.07 / 42"	1.47 / 58"	1.39 / 55"	0.45 / 18"
48" (1.22 m)	1.22 / 48"	1.68 / 66"	1.60 / 63"	0.56 / 22"

Note: All three pellet smoker variants share the same D_eff (0.45 m) and nearly identical z_0 values (-0.38 to -0.30 m). The geometric hood sizing is similar across all three, dominated by the source diameter and height-dependent spread. The difference in Q_c affects velocity and mass flow rate (relevant to CFM sizing in RB-008) but not the geometric plume width for hood sizing purposes.

3.7 Consolidated Recommended Hood Width Summary

For rapid engineering reference, the following consolidated table presents the recommended hood width (W_rec) for all source types at the three most common mounting heights (24", 30", 36").

Table 3.7: Recommended Minimum Hood Width W_rec (inches) — Outdoor Conditions (K = 1.70)

Source Type	24" Height	30" Height	36" Height
Gas Grill — Small	47"	51"	55"
Gas Grill — Medium	53"	57"	61"
Gas Grill — Large	58"	62"	66"
Gas Grill — High-Output	63"	67"	71"
Charcoal Kettle	59"	63"	66"
Charcoal Kettle High	59"	63"	66"
Wood-Fired	53"	57"	60"
Wood-Fired Large	67"	71"	74"
Pellet Smoker Low	50"	54"	58"
Pellet Smoker Medium	50"	54"	58"
Pellet Smoker High	50"	54"	58"

How to use this table: Select the source type and mounting height. The recommended width is the minimum hood width dimension (side to side, parallel to the long axis of the grill) for reliable plume capture in typical outdoor conditions with light wind. The hood depth (front to back) should be at least 6 inches less than the width for rectangular cooking surfaces, or equal to the width for circular sources (kettle grills).

Key insight: The recommended hood widths for outdoor installations are substantially larger than what indoor ventilation practice would suggest. A 30-inch cooking surface at a 30-inch mounting height requires a hood width of at least 57 to 67 inches (depending on source type) for reliable outdoor capture. This is approximately twice the cooking surface width. The physics demands this: the plume at 30 inches is already wider than the cooking surface, and the wind and turbulence margins add further to the required hood extent.

3.8 Entrainment Coefficient Variation with Conditions: Quantitative Summary

This section synthesizes the entrainment coefficient analysis from Sections 2.2 and 3.3 into a reference table for use in downstream topics.

Table 3.8: Entrainment Coefficient alpha for Outdoor Cooking Plume Calculations

Condition	alpha (Gaussian)	Physical Basis	Applicable Domain
Far-field, quiescent, point source	0.083	MTT theory; Papanicolaou & List (1988)	Laboratory reference; not directly applicable
Far-field, quiescent, area source (fire plume)	0.11	Heskestad (2016); SFPE Handbook	Standard engineering value; applicable to outdoor cooking at all hood heights
Near-field, flame region	0.18-0.22	Cetegen et al. (1984)	Within flame zone (z < L_f); not applicable at hood heights for most sources
Transition zone (L_f < z < 3*L_f)	0.12-0.15	Interpolated; Zhou & Gore (1998)	Relevant only for highest-output sources at 18" mounting height
Far-field, light outdoor turbulence (u_rms ~ 0.3 m/s)	0.13-0.15	Hunt (1994); Fisher et al. (1979)	Sheltered patio, very light breeze
Far-field, moderate outdoor turbulence (u_rms ~ 0.5 m/s)	0.15-0.17	Same basis, scaled	Open patio, typical outdoor conditions
Momentum-dominated jet (no buoyancy)	0.057	Ricou & Spalding (1961)	Not applicable to cooking plumes; included for reference

Recommendation for downstream topics: Use alpha = 0.11 for all quiescent-air calculations. For outdoor exposure analysis, use alpha_eff = 0.15 as a representative value that accounts for typical ambient turbulence. The range 0.11 to 0.17 bounds the uncertainty for typical outdoor conditions.

3.9 Open-Air Versus Enclosed: Quantitative Comparison

The entrainment rate and resulting plume properties differ between open-air and enclosed environments. The following comparison quantifies the key differences for a medium gas grill (Q_c = 8.2 kW) at a 30-inch (0.76 m) mounting height.

19

Table 3.9: Open-Air vs. Enclosed Comparison (Gas Grill Medium, 30" Height)

Parameter	Open-Air (Outdoor)	Enclosed (Indoor Kitchen)	Ratio (Outdoor/Indoor)
Effective entrainment coefficient alpha	0.15 (with turbulence)	0.11 (quiescent)	1.36
Entrainment perimeter	Full 360 degrees	Restricted (wall on 1-2 sides)	1.2-1.5x
Effective plume width b_eff	0.18 m	0.14 m	1.3x
Time-averaged capture diameter d_capture	1.05 m (41")	1.05 m (41")	1.0x (same formula)
Effective outdoor capture diameter (with margins)	1.45 m (57")	1.05-1.15 m (41-45")	1.3-1.4x
Mass flow rate at hood m_dot_p	0.093 kg/s (base) + ambient	0.093 kg/s (base)	1.0x (plume itself similar)
Hood CFM required for capture	350-500 CFM (estimated)	200-300 CFM	1.5-2.0x
Escape recovery (plume recirculation)	0% (permanent loss)	30-50% (ceiling jet returns)	0x
Effective single-pass capture efficiency needed	>95%	>60-70% (recirculation compensates)	1.4-1.6x

Critical finding: The fundamental physics of the plume itself (entrainment rate, Gaussian profiles, mass flow) is not dramatically different between indoor and outdoor environments. The SFPE correlations apply in both cases. The difference lies in three factors:

1. **Ambient turbulence increases effective plume width outdoors by approximately 30%.** This requires proportionally larger hood dimensions.
2. **No recirculation recovery outdoors.** In an enclosed kitchen, 30-50% of escaped plume fluid is eventually captured through ceiling jet return, re-entrainment by the hood, or general room recirculation. Outdoors, escaped plume fluid is permanently lost through **Open-Boundary Dilution**. This means the first-pass capture efficiency must be much higher outdoors.
3. **Wind introduces a stochastic displacement** that has no indoor analog. Even modest wind (0.5 m/s) can deflect the plume by 8 inches at a 30-inch mounting height, requiring substantial hood overhang on all sides.

The combined effect is that an outdoor hood must be approximately 1.5 to 2.0 times the size of an equivalent indoor hood for the same source. This quantifies the often-stated but rarely supported claim that "outdoor ventilation is harder than indoor ventilation." The detailed analysis of why indoor assumptions fail outdoors is addressed in RB-004.

---

4. 4. Implications for Outdoor BBQ Ventilation

4.1 Hood Width Is Not Optional — It Is Physics

The entrainment analysis demonstrates that hood width is not a matter of aesthetic preference or manufacturing convenience. It is a physical requirement dictated by the plume spread rate and the entrainment-driven lateral expansion of the **Buoyant Cooking Plume**.

At a 30-inch mounting height, a medium gas grill produces a plume with a recommended outdoor capture width of 57 inches. A hood narrower than this physically cannot capture the full plume under typical outdoor conditions. No amount of additional CFM (exhaust flow rate) can compensate for insufficient width, because increasing exhaust velocity accelerates the air that is within the hood's coverage area but does not extend the hood's lateral reach to plume fluid that is beyond its physical boundary.

This is the distinction between **Momentum-Limited Capture** (where the hood has sufficient area but insufficient velocity to draw in the plume) and geometry-limited capture (where the hood has insufficient area regardless of velocity). For outdoor cooking plumes, geometry-limited capture is the dominant failure mode. The plume has ample velocity to enter the hood; the question is whether the hood extends far enough to intercept the plume's outer boundary.

20

A hood that is too narrow creates a **Missed Plume Region** — the annular zone where plume fluid passes above or beside the hood and escapes irreversibly. The volume of the **Missed Plume Region** increases rapidly as the mismatch between hood width and plume width grows. At 30-inch mounting height, a 36-inch-wide hood over a medium gas grill (plume capture diameter = 41 inches in quiescent conditions, 57 inches with outdoor margin) allows approximately 30-40% of the plume volume to escape through the **Missed Plume Region**. This is a first-order capture failure that cannot be recovered by increasing exhaust CFM.

4.2 Overhang Is the Key Dimension

The required overhang — the distance the hood extends beyond the cooking surface edge — is the most operationally important dimension derived from this analysis. The cooking surface width is fixed by the appliance; the overhang is the adjustable dimension that determines whether the hood captures the plume expansion.

For all source types at all mounting heights, the required overhang is 12 to 26 inches per side. This means the hood must extend 12 to 26 inches beyond the cooking surface edge in every direction (front, back, left, right) to capture the expanded plume with turbulence and wind margin.

The overhang requirement increases with height:

Mounting Height	Typical Required Overhang Per Side
18"	11-16"
24"	13-18"
30"	15-20"
36"	17-22"
48"	21-26"

Practical consequence: A grill that is 24 inches wide, mounted with a hood at 30 inches, requires a hood that extends approximately 17 inches beyond the grill on each side — for a total hood width of approximately 58 inches. The hood is more than twice the width of the grill. This ratio may seem excessive, but it is the direct physical consequence of the entrainment-driven plume expansion quantified in this paper.

4.3 Charcoal and Low-Output Sources Require Disproportionate Hood Coverage

A counterintuitive result of the analysis is that charcoal grills and low-output pellet smokers require nearly as much hood coverage as high-output gas grills. The physical reason is that plume width is governed primarily by the source diameter D_{eff} and the height above the virtual origin, both of which are similar across source types. The difference in Q_c affects plume velocity and temperature (which matter for CFM sizing) but has limited effect on plume width (which matters for hood dimensions).

A charcoal kettle ($Q_c = 1.8$ kW) at 30 inches requires a recommended hood width of 63 inches. A large gas grill ($Q_c = 12.3$ kW) at 30 inches requires 62 inches. The charcoal grill requires the same hood width despite having one-seventh the convective heat release rate. This is because:

1. The charcoal kettle has a large D_{eff} (0.56 m, a 22-inch diameter cooking surface) that dominates the plume width at all heights.
2. The charcoal kettle has a more negative virtual origin ($z_0 = -0.47$ m) that increases the effective height ($z - z_0$) and therefore the entrainment-driven spread.
3. The charcoal plume is weaker and more susceptible to wind displacement, requiring the full outdoor margin factor.

The implication for hood specification is that hood width should be selected based on the cooking surface dimensions and mounting height, not based on the heat release rate or BTU rating. The BTU rating matters for CFM (how much air the hood must exhaust), but the physical hood size is a geometric problem determined by entrainment physics and source geometry.

21

4.4 The Depth Dimension Is Equally Critical

Hood depth (the front-to-back dimension) is often overlooked in hood specification, with attention focused on width. However, the plume is approximately axisymmetric — it expands in all horizontal directions, not just side to side. The front-to-back capture requirement is governed by the same physics as the side-to-side requirement.

For rectangular cooking surfaces (most gas grills), the depth dimension of the cooking surface is typically 14-22 inches, while the width is 18-36 inches. The plume expansion adds the same overhang requirement in both dimensions. A grill that is 22 inches deep at a 30-inch mounting height requires a hood depth of approximately 22 + 2 * 17 = 56 inches. This is a substantial dimension that may conflict with practical installation constraints (proximity to walls, user access, aesthetic considerations).

The front edge of the hood is particularly important because:

1. The cook stands at the front of the grill, and the plume can be entrained into the cook's breathing zone if the hood does not extend sufficiently forward.
2. Many outdoor installations place the grill against a wall, providing a natural rear boundary. The front edge is the only open edge where the plume can escape.
3. Wind commonly approaches from the front or sides in outdoor installations, deflecting the plume rearward. Front overhang is critical for maintaining capture under forward wind conditions.

4.5 The Mounting Height Multiplier Effect

The analysis quantifies a compounding effect of mounting height on hood requirements. Every 6 inches of additional mounting height simultaneously:

1. Increases the required hood width by approximately 4-5 inches (from plume expansion)
2. Increases the required overhang by approximately 2-3 inches per side
3. Increases the required exhaust CFM by approximately 25-40% (from increased plume mass flow)
4. Decreases the plume centerline velocity by approximately 5-8% (from velocity decay)
5. Increases the plume's susceptibility to wind displacement (lower momentum relative to crossflow)

These effects compound multiplicatively: the hood must be wider, deeper, and more powerful to capture a plume that is simultaneously wider, slower, and more easily deflected. This is why mounting height is the single most consequential variable in outdoor hood design, as established in RB-001 and quantitatively reinforced by the entrainment analysis in this paper.

For design purposes, the following mounting height selection guidance emerges:

Mounting Height	Assessment
18" (0.46 m)	Optimal for capture. Smallest hood, lowest CFM. May conflict with fire safety clearance and user headroom. Suitable for low-profile appliances (pellet smokers, small grills).
24" (0.61 m)	Excellent for capture. Moderate hood size. Adequate clearance for most users and appliances. Preferred for residential installations where possible.
30" (0.76 m)	Good for capture. Commonly specified height. Hood requirements begin to become substantial (57-71 inches wide depending on source). Recommended maximum for high-performance installations.
36" (0.91 m)	Acceptable for capture with properly sized hood. Significant CFM and width requirements. Performance degrades noticeably from 30". Acceptable for general-purpose installations.
48" (1.22 m)	Challenging for capture. Very large hood dimensions (66-82 inches) and high CFM (3x the 24" requirement). Not recommended unless physically required by installation constraints. Performance margins are thin.

4.6 Implications for Standard Hood Sizes in the Outdoor Market

The recommended hood widths from Table 3.7 can be compared against standard outdoor hood sizes currently available in the market:

Market Hood Size	Adequacy
36" hood	Suitable only for pellet smokers and small gas grills at 18" mounting height. Inadequate for all other combinations.
42" hood	Suitable for small gas grills at 18-24" mounting height. Inadequate for medium, large, and high-output sources at any standard height.
48" hood	Suitable for small-medium gas grills at 18-24" mounting height, and for pellet smokers at all heights up to 30". Inadequate for large gas grills, charcoal kettles, and wood-fired sources at heights above 24".
54" hood	Suitable for medium gas grills at 24-30" mounting height. Marginal for large gas grills and charcoal kettles at 24".
60" hood	Suitable for most sources at 24-30" mounting height. Marginal for large gas grills and wood-fired sources at 36".
72" hood	Suitable for all sources at all heights up to 36". Adequate for large sources even at 48" height.

Key conclusion: The most common outdoor hood sizes in the consumer market (36-48 inches) are undersized for reliable plume capture at typical mounting heights (30-36 inches) for all source types except pellet smokers and small gas grills. The physics of entrainment and plume spread requires hood widths of 54 to 72 inches for reliable capture of medium to large outdoor cooking sources. This mismatch between market availability and physical requirements is a central finding of this research program and will be further developed in RB-005 (hood geometry effects) and RB-008 (CFM requirements).

---

5. 5. Knowledge Gaps or Opportunities

5.1 Well-Established Knowledge

The following aspects of entrainment and plume spread are well-established and form a reliable basis for the engineering recommendations in this paper:

1. **Morton-Taylor-Turner entrainment theory** is the foundational model for turbulent buoyant plumes and has been validated over seven decades of experimental and theoretical work. The linear growth of plume radius with height is a robust prediction.
2. **Heskestad plume correlations** are the standard engineering tool for fire plume calculations and are validated against extensive experimental data. The plume width, velocity, temperature, and mass flow correlations used in this paper have well-characterized accuracy.
3. **The entrainment coefficient** for far-field buoyant plumes is known to within approximately 15% (alpha = 0.083 to 0.11 depending on profile convention and experimental conditions). This is sufficient accuracy for engineering hood sizing.
4. **Gaussian self-similarity** in the far-field plume region is well-confirmed by experiment. The velocity-to-temperature width ratio lambda approximately equals 1.2 is robustly established.
5. **The puffing frequency** scales with (g/D)^(1/2) with a well-determined proportionality constant. This is a predictable and quantifiable oscillation.

5.2 Areas of Moderate Uncertainty

1. **Turbulent intermittency amplification.** The ratio of instantaneous to time-averaged plume width (1.5 to 2.5x for the 99th percentile) is established for laboratory plumes in quiescent environments. Whether outdoor cooking plumes — with their complex source geometry, variable fuel types, and ambient turbulence — exhibit the same intermittency statistics is not experimentally confirmed. The values used in this paper are extrapolated from laboratory data.
2. **Outdoor turbulence enhancement of entrainment.** The functional form alpha_eff = alpha_0 * (1 + C * u_rms/W_c) is supported by theoretical and limited experimental evidence, but the constant C and the applicable range of u_rms/W_c ratios are not precisely established for cooking plume conditions. The effective outdoor entrainment coefficients used in this paper (alpha_eff = 0.13 to 0.17) carry uncertainty of approximately 20-30%.

3. **Area source correction.** The Heskestad virtual origin formulation converts the distributed cooking surface to an equivalent point source. This is a standard approximation, but its accuracy for wide, low-intensity sources (such as a 22-inch charcoal grill at 4.4 kW) has not been experimentally verified. The virtual origin correction may underestimate the plume width near the source for very wide, low-intensity sources.

4. **Wind margin factors.** The preliminary wind deflection analysis in Section 3.5 (Margin 3) uses a simple Briggs-type plume bending estimate. The actual wind interaction with cooking plumes is complex, involving plume deformation, enhanced entrainment, and vortex shedding effects that are not captured by this simple model. RB-006 will provide a detailed wind interaction analysis; the wind margins in this paper should be treated as preliminary estimates.

5.3 Knowledge Gaps Requiring Further Research

1. **No experimental validation of plume width predictions for outdoor cooking sources.** The plume diameter values in Tables 3.3 and 3.6 are derived entirely from theoretical correlations developed for pool fires and gas burner plumes. No published experimental data validates these predictions for the specific geometry, heat release rates, and fuel types of outdoor barbecue sources. A measurement campaign using thermocouple arrays or PIV (particle image velocimetry) on operating outdoor grills would provide critical validation.

2. **Interaction between plume intermittency and hood capture dynamics.** The time-averaged plume and the instantaneous plume are different entities. The hood does not capture the time-averaged plume; it captures a succession of instantaneous plume realizations. The dynamic interaction between the fluctuating plume boundary and the hood's capture flow field has not been studied for outdoor cooking conditions. This is an important topic for RB-005 (hood geometry effects).

3. **Effect of food, grease, and cooking byproducts on plume spread.** The plume correlations assume a clean buoyant plume from a heat source. Real cooking plumes contain grease aerosol, water vapor from food moisture, and particulate matter from fuel combustion. These constituents may alter the plume density, viscosity, and turbulent structure in ways not captured by the clean-plume correlations. The magnitude of these effects is unknown.

4. **Combined entrainment and wind effects.** The margin analysis in Section 3.5 treats turbulent intermittency, puffing, and wind deflection as independent, multiplicative factors. In reality, these effects interact: wind increases turbulence intensity, which increases intermittency, which amplifies the instantaneous plume width. The combined effect may be larger or smaller than the product of individual factors. RB-006 will address wind interaction in detail, but the coupling with intermittency remains a gap.

5. **Non-axisymmetric plume effects.** Rectangular cooking surfaces produce plumes that are initially non-axisymmetric (wider in the long dimension). The transition to axisymmetric Gaussian profiles occurs at some height that depends on the aspect ratio. For cooking surfaces with aspect ratios of 1.5:1 to 2:1 (common for gas grills), the plume may remain significantly non-axisymmetric at low mounting heights. The Heskestad correlations assume axisymmetric plumes. Hood sizing should account for the possibility that the plume is wider in the grill's long dimension than the axisymmetric prediction suggests.

6. **Coupled hood-plume flow dynamics.** The analysis in this paper treats the plume as if the hood were not present. In reality, the hood's exhaust flow creates a suction field that modifies the plume trajectory, potentially narrowing it (drawing the plume inward) or widening it (if the suction creates local crossflows). This coupled system is addressed in RB-005 and RB-008 but represents a significant complexity not captured in the present stand-alone plume analysis.

---

6. 6. Diagram Mapping Notes (Text Only)

The following diagram descriptions are aligned with the Diagram Standard v2.1 canonical diagram types and should be produced by the Diagram & Visual Communication Agent.

Diagram 6.1: Entrainment Rate Profile Along Plume Height (Diagram Type 2 — Quantitative Chart)

Purpose: Illustrate how the local entrainment rate dm_dot/dz varies with height for representative cooking sources, showing that the plume ingests progressively more ambient air per unit height as it rises.

Content:

- X-axis: height above cooking surface z (0 to 1.30 m / 0 to 51 inches)
- Y-axis: local entrainment rate dm_dot/dz (kg/s per meter), range 0 to 0.35
- Curves for five representative sources: Gas Grill Medium (Q_c = 8.2 kW), Gas Grill Large (Q_c = 12.3 kW), Gas Grill High-Output (Q_c = 16.4 kW), Charcoal Kettle (Q_c = 1.8 kW), Pellet Smoker Low (Q_c = 1.5 kW)
- Each curve follows dm_dot/dz = 0.118 * Q_c^(1/3) * z^(2/3)
- Vertical dashed lines at standard hood heights: 18", 24", 30", 36", 48"
- Annotation at 30" height: "At 30 inches, a medium gas grill entrains 0.19 kg/s per meter of height — approximately 5x the original source mass flow"
- Shaded region below curves from 0 to z represents cumulative entrained mass (visual indication of the "entrainment tax")
- Figure caption: "Figure 2.1: Local entrainment rate as a function of height for representative outdoor cooking sources. The entrainment rate increases with height as z^(2/3), reflecting the growing plume perimeter. Stronger sources (higher Q_c) entrain air at proportionally higher rates."

Diagram 6.2: Gaussian vs. Top-Hat Plume Profile Comparison (Diagram Type 1 — Plume Cross-Section)

Purpose: Clearly illustrate the difference between the Gaussian and top-hat profile assumptions and their implications for defining "plume width."

Content:

- Horizontal axis: radial distance r from plume centerline (-3*b_T to +3*b_T)
- Vertical axis: normalized velocity or temperature (0 to 1.0)
- Gaussian profile: smooth bell curve W/W_c = exp(-r^2/b_u^2) with b_u marked
- Top-hat profile: rectangular function with b_TH = b_u * sqrt(2) marked
- Both profiles have equal area under the curve (equal flux)
- Shaded regions showing:
    - Inner region (r < b_T): "63% of buoyancy flux" — always captured
    - Middle region (b_T < r < 2*b_T): "35% of buoyancy flux" — requires sized hood
    - Outer region (r > 2*b_T): "2% of buoyancy flux" — intermittent, turbulent excursions
- Intermittency fraction gamma(r) plotted on secondary axis, showing how the fraction of time plume is present decreases with radial distance
- Figure caption: "Figure 2.2: Comparison of Gaussian and top-hat velocity profiles for a buoyant plume cross-section. The Gaussian profile (solid) captures the realistic radial decay; the top-hat profile (dashed) is a simplified equivalent. The intermittency fraction (dotted) shows that plume fluid is present less than 50% of the time at the Gaussian 1/e radius."

Diagram 6.3: Instantaneous Versus Time-Averaged Plume Boundary (Diagram Type 1 — Plume Profile)

Purpose: Show the critical distinction between the smooth, conical time-averaged plume envelope and the irregular, fluctuating instantaneous plume boundary.

Content:

- Vertical plume from cooking surface to 48" (1.22 m)
- Time-averaged Gaussian envelope shown as smooth conical boundary (solid line) expanding at b_T = 0.12(z - z_0)
- 98% flux capture contour shown as slightly wider conical boundary (dashed line) at 2.0 * b_T

25

- Instantaneous plume boundary shown as a wavy, irregular line (multiple realizations overlaid as semi-transparent contours) that fluctuates between 0.5*b_T and 2.5*b_T
- 99th percentile instantaneous extent shown as outermost boundary (dotted line) at approximately 3.0 * b_T
- Annotations:
    - "Time-averaged Gaussian: smooth, predictable"
    - "Instantaneous: irregular, turbulent — the **real** plume boundary"
    - "Turbulent excursions reach 2-2.5x the mean radius"
    - "Hood must capture the instantaneous plume, not just the average"
- Figure caption: "Figure 2.3: Time-averaged versus instantaneous plume boundaries. The time-averaged plume (solid boundary) is a smooth cone, but the actual instantaneous plume (irregular boundaries) fluctuates widely due to turbulent intermittency. A hood sized only to the time-averaged boundary will intermittently fail to capture plume excursions."

Diagram 6.4: Hood Sizing Visualization for Medium Gas Grill at Three Heights (Diagram Type 3 — Hood-Plume Geometry)

Purpose: Show the recommended hood dimensions relative to the cooking surface and plume for a medium gas grill at 24", 30", and 36" mounting heights.

Content:

- Three side-by-side plan-view (top-down) diagrams, one for each height
- Cooking surface shown as a rectangle (24" x 21") at center
- Time-averaged plume cross-section at hood height shown as a circle (dashed line)
- Recommended hood footprint shown as a rectangle (solid line) encompassing the plume
- Overhang dimensioned on each side
- At 24": cooking surface 24"x21", plume circle diameter 39", hood 53"x49"
- At 30": cooking surface 24"x21", plume circle diameter 41", hood 57"x53"
- At 36": cooking surface 24"x21", plume circle diameter 44", hood 61"x57"
- Hatched region between plume boundary and hood edge labeled "Safety margin for turbulence and wind"
- Annotations showing overhang dimensions: "15" overhang at 24"" increasing to "19" overhang at 36""
- Figure caption: "Figure 3.1: Recommended hood dimensions for a medium gas grill (cooking surface 24 x 21 inches) at three mounting heights. The hood must extend well beyond the cooking surface to capture the entrained plume with margin for turbulence and **Wind-Affected Plume Behavior**."

Diagram 6.5: Overhang Requirement Versus Mounting Height (Diagram Type 2 — Quantitative Chart)

Purpose: Show how the required overhang increases with mounting height, providing a quick-reference chart for installers.

Content:

- X-axis: mounting height (18" to 48")
- Y-axis: required overhang per side (inches), range 8" to 28"
- Curves for: Gas Grill Small, Gas Grill Large, Charcoal Kettle, Pellet Smoker
- The curves are approximately parallel, reflecting the linear plume growth
- Annotation: "Every 6 inches of mounting height adds approximately 2-3 inches to the required overhang per side"
- Shaded region below 12" overhang labeled "Insufficient for reliable outdoor capture"
- Shaded region above 20" overhang labeled "Large hoods required — consider reducing mounting height instead"

26

- Figure caption: "Figure 3.2: Required hood overhang per side as a function of mounting height. The overhang increases approximately linearly with height, reflecting the linear plume expansion. At heights above 36 inches, the overhang requirement becomes large enough that reducing mounting height is typically more practical than increasing hood size."

Diagram 6.6: Open-Air vs. Enclosed Entrainment Comparison (Diagram Type 4 — Comparative/Conceptual)

Purpose: Visually compare the entrainment and capture dynamics between an indoor kitchen installation and an outdoor open-air installation.

Content:

- Left panel: Indoor kitchen — plume rising from cooktop, walls on 2-3 sides, ceiling above, hood at 30"
  - Restricted entrainment arrows (blocked by walls)
  - Ceiling jet arrows showing escaped plume redirected along ceiling back toward hood
  - Label: "Walls restrict entrainment. Ceiling redirects escaped plume. Room pressurization assists capture."
  - Effective capture zone labeled as **Effective Capture Area**
- Right panel: Outdoor patio — plume rising from grill, no walls, open sky, hood at 30"
  - Full 360-degree entrainment arrows
  - Escaped plume gas dispersing freely upward and laterally
  - Wind arrows showing lateral deflection
  - Label: "No walls — maximum entrainment. No ceiling — no recovery. **Open-Boundary Dilution** means every escape is permanent."
  - Wider hood shown with larger overhang
- Center annotation: "Same grill. Same BTU. But outdoor capture requires 1.5-2x larger hood and higher CFM."
- Figure caption: "Figure 4.1: Comparison of entrainment and capture dynamics between indoor (left) and outdoor (right) installations. The absence of walls, ceiling, and room confinement in the outdoor environment increases plume spread, eliminates secondary capture mechanisms, and introduces **Wind-Affected Plume Behavior** — all of which demand larger hood dimensions and higher exhaust rates."

---

7. Appendix A: Calculation Methodology and Input Parameters

A.1 Input Parameters from RB-001

All source-specific parameters (Q_c, D_{eff}, z_0) are taken directly from RB-001 Tables 3.1 and 3.2. The following table reproduces these inputs for reference:

Source Type	Q_c (kW)	D_eff (m)	z_0 (m)	L_f (m)
Gas Grill — Small	5.1	0.43	-0.30	< 0
Gas Grill — Medium	8.2	0.51	-0.37	~0
Gas Grill — Large	12.3	0.58	-0.41	0.14
Gas Grill — High-Output	16.4	0.65	-0.44	0.26
Charcoal Kettle	1.8	0.56	-0.47	< 0
Charcoal Kettle High	3.5	0.56	-0.41	< 0
Wood-Fired	7.6	0.50	-0.36	~0
Wood-Fired Large	13.3	0.70	-0.48	0.09
Pellet Smoker Low	1.5	0.45	-0.38	< 0
Pellet Smoker Medium	3.4	0.45	-0.32	< 0
Pellet Smoker High	5.7	0.45	-0.30	~0

A.2 Standard Ambient Conditions

Parameter	Symbol	Value	Units
Ambient temperature	T_inf	293	K (20 degrees C / 68 degrees F)
Gravitational acceleration	g	9.81	m/s^2
Ambient air density	rho_inf	1.20	kg/m^3
Specific heat of air	c_p	1.00	kJ/(kg*K)
Entrainment coefficient (far-field, quiescent)	alpha	0.11	dimensionless
Entrainment coefficient (far-field, outdoor)	alpha_eff	0.15	dimensionless

A.3 Key Formulas Used

Calculation	Formula	Source
Local entrainment rate	dm_dot/dz = 0.118 * Q_c^(1/3) * z^(2/3)	Derivative of Heskestad mass flow
Gaussian temperature half-width	b_T = 0.12 * (z - z_0)	Heskestad (2016)
Mean plume diameter (90% flux)	d_mean = 3.0 * b_T = 0.36 * (z - z_0)	1.5 * b_T radius, both sides
Heskestad capture diameter (98% flux)	d_capture = 0.48 * (z - z_0) + D_eff	Heskestad (2016); includes source
99th percentile instantaneous diameter	d_99 = 0.72 * (z - z_0) + D_eff	3.0 * b_T radius, both sides, plus D_eff
Puffing frequency	f_puff = 0.47 * (g / D_eff)^(1/2)	Cetegen & Kasper (1996)
Outdoor margin factor (recommended)	K = 1.70	This paper, Section 3.5
Recommended hood width	W_rec = K * d_capture	This paper
Required overhang per side	OH = (W_rec - cooking surface width) / 2	Geometric

A.4 Cooking Surface Dimensions Used

Source Type	Cooking Surface (W x D, inches)	Shape
Gas Grill — Small	18 x 19	Rectangular
Gas Grill — Medium	24 x 21	Rectangular
Gas Grill — Large	30 x 22	Rectangular
Gas Grill — High-Output	36 x 22	Rectangular
Charcoal Kettle	22 diameter	Circular
Charcoal Kettle High	22 diameter	Circular
Wood-Fired	24 x 16	Rectangular
Wood-Fired Large	36 x 24	Rectangular
Pellet Smoker Low	22 x 14	Rectangular
Pellet Smoker Medium	22 x 14	Rectangular
Pellet Smoker High	22 x 14	Rectangular

8. Appendix B: Comprehensive Hood Sizing Quick-Reference (Imperial Units)

This appendix provides a single consolidated lookup table for the recommended hood dimensions at the three most commonly specified mounting heights, in imperial units only, for rapid field reference.

Table B.1: Recommended Hood Dimensions at 24" Mounting Height

Source Type	Hood Width	Hood Depth	Overhang (each side)
Gas Grill — Small	47"	45"	14"
Gas Grill — Medium	53"	49"	15"
Gas Grill — Large	58"	51"	14"
Gas Grill — High-Output	63"	53"	13"
Charcoal Kettle	59"	59"	18"
Charcoal Kettle High	59"	59"	18"
Wood-Fired	53"	48"	15"
Wood-Fired Large	67"	55"	15"
Pellet Smoker (all)	50"	47"	14"

29

Table B.2: Recommended Hood Dimensions at 30" Mounting Height

Source Type	Hood Width	Hood Depth	Overhang (each side)
Gas Grill — Small	51"	49"	16"
Gas Grill — Medium	57"	53"	17"
Gas Grill — Large	62"	55"	16"
Gas Grill — High-Output	67"	57"	15"
Charcoal Kettle	63"	63"	20"
Charcoal Kettle High	63"	63"	20"
Wood-Fired	57"	52"	17"
Wood-Fired Large	71"	59"	17"
Pellet Smoker (all)	54"	51"	16"

Table B.3: Recommended Hood Dimensions at 36" Mounting Height

Source Type	Hood Width	Hood Depth	Overhang (each side)
Gas Grill — Small	55"	53"	18"
Gas Grill — Medium	61"	57"	19"
Gas Grill — Large	66"	59"	18"
Gas Grill — High-Output	71"	61"	17"
Charcoal Kettle	66"	66"	22"
Charcoal Kettle High	66"	66"	22"
Wood-Fired	60"	56"	18"
Wood-Fired Large	74"	63"	19"
Pellet Smoker (all)	58"	55"	18"

9. Appendix C: Dilution Ratio and Entrainment Efficiency Summary

Table C.1: Fraction of Plume Mass That Is Entrained Ambient Air

Height	Gas Small	Gas Medium	Gas Large	Charcoal Kettle	Pellet Low
18"	93%	91%	90%	94%	94%
24"	95%	94%	93%	96%	96%
30"	97%	96%	95%	97%	97%
36"	98%	97%	97%	98%	98%
48"	99%	98%	98%	99%	99%

These values quantify the "entrainment tax" — at 30 inches, 95-97% of the air the hood must capture is clean ambient air that was not originally part of the plume. The contaminants (smoke, grease, combustion byproducts) constitute only 3-5% of the plume mass at this height. The hood must exhaust the entire volume — contaminants and entrained air together — because there is no practical mechanism to selectively extract contaminants from the mixed plume at the **Plume Interception Plane**.

30

10. Appendix D: Unit Conversion Reference

Quantity	SI	Imperial
Heat release rate	1 kW	3,412 BTU/hr
Velocity	1 m/s	197 ft/min
Length	1 m	39.37 inches
Mass flow rate	1 kg/s	2.205 lb/s
Mass entrainment rate	1 kg/(s*m)	0.672 lb/(s*ft)
Temperature	Delta_T (K) = Delta_T (degrees C)	Delta_T (degrees F) = 1.8 * Delta_T (K)

---

11. References

1. Morton, B.R., Taylor, G.I., and Turner, J.S. (1956). "Turbulent gravitational convection from maintained and instantaneous sources." *Proceedings of the Royal Society A*, 234, pp. 1-23.
2. Ricou, F.P. and Spalding, D.B. (1961). "Measurements of entrainment by axisymmetrical turbulent jets." *Journal of Fluid Mechanics*, 11(1), pp. 21-32.
3. George, W.K., Alpert, R.L., and Tamanini, F. (1977). "Turbulence measurements in an axisymmetric buoyant plume." *International Journal of Heat and Mass Transfer*, 20(11), pp. 1145-1154.
4. McCaffrey, B.J. (1979). "Purely Buoyant Diffusion Flames: Some Experimental Results." NBSIR 79-1910, National Bureau of Standards.
5. Cetegen, B.M., Zukoski, E.E., and Kubota, T. (1984). "Entrainment in the near and far field of fire plumes." *Combustion Science and Technology*, 39, pp. 305-331.
6. Papanicolaou, P.N. and List, E.J. (1988). "Investigations of round vertical turbulent buoyant jets." *Journal of Fluid Mechanics*, 195, pp. 341-391.
7. Panchapakesan, N.R. and Lumley, J.L. (1993). "Turbulence measurements in axisymmetric jets of air and helium. Part 1. Air jet." *Journal of Fluid Mechanics*, 246, pp. 197-223.
8. Shabbir, A. and George, W.K. (1994). "Experiments on a round turbulent buoyant plume." *Journal of Fluid Mechanics*, 275, pp. 1-32.
9. Hunt, G.R. (1994). "The Effect of External Turbulence on Plumes." PhD Thesis, University of Cambridge.
10. Zukoski, E.E. (1995). "Properties of Fire Plumes." In *Combustion Fundamentals of Fire*, ed. G. Cox, Academic Press.
11. Cetegen, B.M. and Kasper, K.D. (1996). "Experiments on the oscillatory behavior of buoyant plumes of helium and helium-air mixtures." *Physics of Fluids*, 8(11), pp. 2974-2984.
12. Zhou, X. and Gore, J.P. (1998). "Air entrainment flow field induced by a pool fire." *Combustion and Flame*, 100(1-2), pp. 52-60.
13. Wang, H.W. and Law, A.W.K. (2002). "Second-order integral model for a round turbulent buoyant jet." *Journal of Fluid Mechanics*, 459, pp. 397-428.
14. Fischer, H.B., List, E.J., Koh, R.C.Y., Imberger, J., and Brooks, N.H. (1979). *Mixing in Inland and Coastal Waters*. Academic Press.
15. Gifford, F.A. (1961). "Use of routine meteorological observations for estimating atmospheric dispersion." *Nuclear Safety*, 2(4), pp. 47-51.
16. Pasquill, F. and Smith, F.B. (1983). *Atmospheric Diffusion*, 3rd ed. Ellis Horwood Ltd.

31

17. Philip, J. and Marusic, I. (2012). "Large-scale eddies and their role in entrainment in turbulent jets and wakes." *Physics of Fluids*, 24, 055108.

18. da Silva, C.B., Hunt, J.C.R., Eames, I., and Westerweel, J. (2014). "Interfacial layers between regions of different turbulence intensity." *Annual Review of Fluid Mechanics*, 46, pp. 567-590.

19. Heskestad, G. (2016). "Fire Plumes, Flame Height, and Air Entrainment." Chapter 13, *SFPE Handbook of Fire Protection Engineering*, 5th ed. Springer.

20. ASHRAE (2019). *ASHRAE Handbook — HVAC Applications*, Chapter 33: Kitchen Ventilation.

21. Drysdale, D. (2011). *An Introduction to Fire Dynamics*, 3rd ed. John Wiley & Sons.

22. Briggs, G.A. (1984). "Plume rise and buoyancy effects." In *Atmospheric Science and Power Production*, ed. D. Randerson, DOE/TIC-27601.

This document is a research output of the Outdoor Ventilation Standard, governed by the Research Program Charter v2.6. All terms are used as defined in Glossary v1.1. This paper builds upon the foundational plume characterization established in RB-001 and provides the engineering hood sizing tables that downstream topics RB-003, RB-004, RB-005, and RB-008 will reference.

32