RB-001

RB-001: Buoyant Plume Behavior from Barbecue and High-Heat Cooking Sources

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Outdoor Ventilation Standard

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1. 1. Topic Definition

This paper characterizes the **Buoyant Cooking Plume** generated by the four principal outdoor barbecue and high-heat cooking source types: gas grills, charcoal grills, wood-fired grills, and pellet smokers. The scope encompasses the full vertical development of the plume from the cooking surface to heights relevant to hood capture, specifically 18 inches (0.46 m) through 48 inches (1.22 m) above the cooking surface.

The central objective is to provide quantitative, physics-grounded values for the following plume parameters as a function of height and source type:

1. Convective heat release rate (Q_c) and total heat release rate (Q_total)
2. Centerline temperature excess above ambient (Delta_T_0)
3. Centerline vertical velocity (u_0)
4. Plume radius at the 1/e Gaussian decay point
5. Plume mass flow rate (m_dot_p)
6. Transition height from the **Near-Field Plume Region** to the self-similar far-field regime

These parameters govern the behavior of the **Buoyant Cooking Plume** at every height of interest and directly determine the requirements for hood sizing, mounting height selection, and exhaust rate specification addressed in subsequent research topics (RB-002 through RB-012).

Problem Framing

Outdoor cooking appliances release thermal energy through combustion of fuel and radiative/convective heating of food, cookware, and surrounding air. The heated gas mixture rises as a turbulent buoyant plume, entraining ambient air and expanding laterally with height. The plume carries combustion byproducts, aerosolized grease particulates, and gaseous cooking effluent. The purpose of a ventilation hood is to intercept this plume at the **Plume Interception Plane** before it disperses into the ambient atmosphere via **Open-Boundary Dilution**.

The fundamental challenge is that the plume's properties at the point of interception — its temperature, velocity, diameter, and contaminant concentration — are strong functions of the source heat release rate and the vertical distance traveled. Every incremental increase in mounting height reduces centerline velocity, reduces temperature excess, and increases plume diameter, progressively degrading the conditions for successful capture.

This paper establishes the quantitative relationships that govern this degradation.

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2. 2. Relevant Physical Principles

2.1 Morton-Taylor-Turner (MTT) Entrainment Theory

The foundational model for turbulent buoyant plumes was established by Morton, Taylor, and Turner (1956). The MTT model rests on three assumptions:

Assumption 1 — Entrainment Hypothesis: The rate at which ambient fluid is entrained into the plume at any height is proportional to the local mean centerline vertical velocity. The proportionality constant is the entrainment coefficient, alpha:

```
U_e = alpha * W_c
```

where U_e is the horizontal inflow velocity at the plume edge and W_c is the local centerline vertical velocity. This is the defining closure assumption of the model.

Assumption 2 — Self-Similarity: At sufficient distance from the source, the plume develops Gaussian radial profiles of velocity and buoyancy (temperature excess) that maintain constant shape with height, differing only in amplitude and width.

Assumption 3 — Boussinesq Approximation: The density difference between plume fluid and ambient air is small relative to the ambient density, so density variations are neglected except in the buoyancy term. This assumption is valid in the far-field but breaks down in the near-field where temperature excess can be hundreds of degrees.

Under these assumptions, the MTT integral equations yield the following self-similar solutions for a pure buoyant plume from a point source:

- Plume radius grows linearly with height: b = (6/5) * alpha * z
- Centerline velocity decays as z^(-1/3)
- Centerline temperature excess decays as z^(-5/3)
- Mass flux increases as z^(5/3)

Entrainment Coefficient Values:

The entrainment coefficient alpha has been extensively measured in laboratory and fire plume experiments. The following values represent the current consensus:

Plume Regime	Entrainment Coefficient (alpha)	Source
Pure buoyant plume (far-field, non-combusting)	0.10 - 0.13	Morton, Taylor & Turner (1956); multiple confirmations
Fire plume (far-field, above flames)	0.09 - 0.10	Cetegen et al. (1982); Zukoski (1995)
Fire plume (flame region)	0.18 - 0.22	Cetegen et al. (1982)
Forced plume / jet	0.05 - 0.08	Fischer et al. (1979)

For outdoor cooking plumes, the far-field non-combusting value of alpha = 0.10 to 0.13 is applicable at heights above the flame tips, while the elevated flame-region value of alpha = 0.18 to 0.22 applies within the near-field combustion zone. This paper uses alpha = 0.11 as the reference value for far-field calculations, consistent with the SFPE Handbook recommendation for fire plumes above the flame region.

2.2 Heskestad Plume Correlations

Gunnar Heskestad developed the most widely applied engineering correlations for axisymmetric fire plumes, published in successive editions of the SFPE Handbook of Fire Protection Engineering. These correlations are validated against extensive fire test data and provide closed-form expressions for plume properties as functions of convective heat release rate and height.

Flame Height:

```
L_f = 0.235 * Q_total^(2/5) - 1.02 * D
```

where L_f is the mean flame height (m), Q_total is total heat release rate (kW), and D is the effective fire diameter (m). This correlation defines the boundary between the combusting (near-field) and non-combusting (far-field) regions of the plume.

Virtual Origin:

```
z_0 = 0.083 * Q_total^(2/5) - 1.02 * D
```

where z_0 is the elevation of the virtual point source origin (m) relative to the actual fire surface. The virtual origin accounts for the finite source geometry, allowing the distributed cooking surface to be modeled as an equivalent point source for far-field calculations.

Centerline Temperature Rise (above flame tips, z > L_f):

```
Delta_T_0 = 9.1 * (T_inf / (g * c_p^2 * rho_inf^2))^(1/3) * Q_c^(2/3) * (z - z_0)^(-5/3)
```

Substituting standard ambient conditions (T_inf = 293 K, g = 9.81 m/s^2, c_p = 1.0 kJ/(kg*K), rho_inf = 1.2 kg/m^3):

```
Delta_T_0 = 25.0 * Q_c^(2/3) * (z - z_0)^(-5/3) [K]
```

This gives the temperature excess above ambient at the plume centerline as a function of convective heat release rate and height above the virtual origin.

Centerline Velocity (above flame tips, z > L_f):

From the self-similar plume solution, the centerline velocity in the far-field plume is:

```
u_0 = 3.4 * (g / (c_p * rho_inf * T_inf))^(1/3) * Q_c^(1/3) * (z - z_0)^(-1/3)
```

Substituting standard ambient conditions:

```
u_0 = 1.03 * Q_c^(1/3) * (z - z_0)^(-1/3) [m/s]
```

This is the **Velocity Decay** relationship — the centerline velocity falls as the inverse one-third power of height above the virtual origin. The decay is gradual compared to temperature (which falls as the inverse five-thirds power), meaning the plume retains significant upward momentum at heights where its temperature excess has become modest.

Plume Mass Flow Rate (above flame tips, z > L_f):

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

Plume Mass Flow Rate (below flame tips, $z < L_f$):

```
m_dot_p = 0.032 * Q_c^(3/5) * z [kg/s]
```

The mass flow rate above the flames increases rapidly with height (as $z^{(5/3)}$) because entrainment continuously adds ambient air mass to the plume. This has a critical ventilation implication: the total volumetric flow that the hood must capture grows substantially with every increment of mounting height.

Plume Width:

The Gaussian plume profile has a temperature half-width b_T and velocity half-width b_u. Heskestad defines the plume radius at the 1/e decay point of the Gaussian profile. The plume width for the temperature profile (to the point where excess temperature falls to approximately 0.5 of centerline value) is:

```
b_T = 0.12 * (T_0 / T_inf)^(1/2) * (z - z_0)
```

For weakly buoyant conditions in the far-field (T_0 / T_{inf} approaching 1):

```
b_T approximately equals 0.12 * (z - z_0)
```

This corresponds to a half-angle of approximately 6.8 degrees for the temperature profile, or a total visible plume cone angle of approximately 13 to 15 degrees. This is consistent with the MTT prediction of $b = (6/5) * \alpha * z$ with $\alpha = 0.10$.

For practical engineering purposes, the plume diameter at height z above the cooking surface is:

```
d_plume = 2 * b_T = 0.24 * (z - z_0)
```

However, for hood sizing, the plume must be captured with margin for turbulent fluctuations, puffing, and wind perturbation. The effective plume diameter for capture purposes is typically taken as:

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```
d_capture = 0.48 * z + D_source
```

where D_source is the effective diameter of the cooking surface and the factor of 0.48 accounts for approximately twice the mean Gaussian radius to capture the majority of contaminant mass, plus margin.

2.3 McCaffrey's Plume Zone Classification

McCaffrey (1979) identified three distinct zones in a buoyant diffusion flame plume, each with characteristic scaling behavior:

Zone 1 — Continuous Flame Region:

- Extends from the fuel surface to approximately 0.4 * L_f
- Temperature is approximately constant near 800-900 degrees C
- Velocity increases with height as z^(1/2)
- Active combustion occurs throughout this zone
- For cooking sources, this zone is typically confined to the space between the burner/coal bed and the cooking grate, plus the immediate volume above the grate

Zone 2 — Intermittent Flame Region:

- Extends from approximately 0.4 * L_f to L_f (the mean flame tip)
- Temperature declines steadily with height
- Velocity is approximately constant or weakly declining
- Intermittent flame tongues penetrate into this zone at varying heights
- This is a transitional zone where combustion is incomplete and variable
- For cooking sources, this zone typically extends from the grate level to 0.2-0.5 m above the grate, depending on heat release rate

Zone 3 — Buoyant Plume Region (Far-Field):

- Extends above L_f to arbitrary height
- Temperature excess decays as z^(-5/3)
- Velocity decays as z^(-1/3)
- No combustion; purely buoyant, entrained flow

- Self-similar Gaussian profiles are established
- This is where the Heskestad far-field correlations apply directly

The transition from Zone 2 to Zone 3 defines the onset of the self-similar far-field regime. Below this transition, the plume is in the **Near-Field Plume Region** where the Boussinesq approximation is invalid and the correlations above must be applied with caution. The transition height is directly governed by the flame height L_f, which is itself a function of total heat release rate and source diameter.

2.4 Convective Heat Fraction

Not all thermal energy released by combustion drives plume buoyancy. The total heat release rate Q_total is partitioned into:

- **Convective fraction (chi_c):** The portion delivered to the plume gases as sensible heat, driving buoyancy. This is Q_c = chi_c * Q_total.
- **Radiative fraction (chi_r):** The portion emitted as thermal radiation to the surroundings (food, cookware, hood, adjacent surfaces, sky). This is Q_r = chi_r * Q_total.
- **Conductive and other losses:** Heat conducted into the grill body, grate, and fuel bed.

For fire plume calculations, the convective fraction is the critical parameter. The convective fraction varies by fuel type and combustion mode:

Fuel Type	Convective Fraction (chi_c)	Radiative Fraction (chi_r)	Notes
Natural gas / propane (premixed burner)	0.60 - 0.75	0.20 - 0.30	Lower soot; cleaner combustion
Charcoal (glowing bed, no flame)	0.30 - 0.50	0.40 - 0.55	Dominant radiant emission from glowing surface
Charcoal (with active flames)	0.50 - 0.65	0.25 - 0.40	Flame combustion shifts energy to convective
Wood (flaming combustion)	0.55 - 0.70	0.25 - 0.35	Higher soot increases radiative fraction
Wood pellets (forced-air combustion)	0.60 - 0.70	0.20 - 0.30	Controlled combustion similar to gas

A commonly used default in fire engineering when specific data is unavailable is chi_c = 0.70 (i.e., 70% convective, 30% radiative). This paper uses fuel-specific convective fractions as stated in the table above, with a default of 0.70 for gas, 0.40 for charcoal in glowing mode, and 0.65 for wood-fired and pellet sources.

Critical Note: The convective fraction for charcoal grills operating in glowing-ember mode (low flame, radiant cooking) is substantially lower than for gas or wood-fired sources. This means that a charcoal grill with the same total BTU output as a gas grill produces a weaker buoyant plume with lower centerline velocity and temperature excess. The radiative energy goes directly to the food and surroundings, not into the rising gas column. This has direct implications for ventilation: the plume from a charcoal grill is weaker than its BTU rating would suggest, but the radiant heat flux at the hood surface is higher.

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3. 3. Observed or Expected Behavior

3.1 Heat Release Rates of Common Outdoor Cooking Appliances

The following table presents representative total heat release rates and derived convective heat release rates for the four principal outdoor cooking source types. Values are based on published manufacturer data for BTU ratings, fire science literature on combustion rates, and standard fuel energy content values.

Assumptions and Basis:

- Gas grill BTU ratings are manufacturer-stated maximum burner output (fuel input rate). Actual thermal release at the cooking surface is lower due to incomplete combustion and losses, but the stated BTU rating represents the fuel energy release rate available for plume generation.
- Charcoal heat release is calculated from fuel consumption rate and specific energy content: briquettes at approximately 29 MJ/kg (12,500 BTU/lb); lump hardwood charcoal at approximately 33 MJ/kg (14,200 BTU/lb).
- Wood-fired values assume hardwood fuel at approximately 19 MJ/kg (8,200 BTU/lb) with active flaming combustion.
- Pellet smoker values are based on pellet consumption rates at various temperature settings; wood pellets contain approximately 18-20 MJ/kg (8,000-8,600 BTU/lb).

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Table 3.1: Representative Heat Release Rates

Source Type	Configuration	Q_total (BTU/hr)	Q_total (kW)	chi_c	Q_c (kW)	D_eff (m)
Gas Grill — Small	2 burners, 350 sq in	25,000	7.3	0.70	5.1	0.43
Gas Grill — Medium	3-4 burners, 500 sq in	40,000	11.7	0.70	8.2	0.51
Gas Grill — Large	4-6 burners, 650 sq in	60,000	17.6	0.70	12.3	0.58
Gas Grill — High-Output	6+ burners or infrared sear	80,000	23.4	0.70	16.4	0.65
Charcoal Grill — Kettle	22" diameter, 2 kg fuel	15,000	4.4	0.40	1.8	0.56
Charcoal Grill — Kettle (high)	22" diameter, 4 kg fuel	30,000	8.8	0.40	3.5	0.56
Charcoal Grill — Kamado	18" diameter, 3 kg lump	25,000	7.3	0.45	3.3	0.46
Wood-Fired Grill	Open grate, active fire	40,000	11.7	0.65	7.6	0.50
Wood-Fired Grill (large)	Argentine-style, large bed	70,000	20.5	0.65	13.3	0.70
Pellet Smoker — Low	Smoking mode, 225 deg F	8,000	2.3	0.65	1.5	0.45
Pellet Smoker — Medium	Roasting mode, 350 deg F	18,000	5.3	0.65	3.4	0.45
Pellet Smoker — High	Grilling mode, 450+ deg F	30,000	8.8	0.65	5.7	0.45

Notes on Table 3.1:

1. D_eff is the effective diameter of the cooking surface, used in the Heskestad virtual origin and flame height calculations. For rectangular cooking surfaces, D_eff = (4A/pi)^(1/2) where A is the cooking surface area.

2. The charcoal grill convective fraction of 0.40 reflects the dominant radiant-cooking mode typical of charcoal operation. During initial lighting and active flaming (e.g., when fat drips onto coals), the convective fraction transiently rises toward 0.55-0.65. The steady-state glowing-ember value of 0.40 represents the conservative condition for plume strength estimation.

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3. Gas grill BTU ratings represent the maximum burner capacity. During normal cooking, burners may operate at 50-75% of rated capacity, and not all burners may be active simultaneously. The values in this table represent full-capacity operation, which is the condition producing the strongest plume and therefore the design condition for hood sizing.
4. Pellet smoker values span a wide range because pellet consumption rate varies from approximately 0.5 lb/hr in low-smoke mode to approximately 2.5 lb/hr or more in high-temperature grilling mode. The heat release rate is directly proportional to pellet consumption.

3.2 Flame Height and Virtual Origin Calculations

Applying the Heskestad correlations to each source type:

Table 3.2: Flame Height and Virtual Origin

Source Type	Q_total (kW)	D_eff (m)	L_f (m)	L_f (in)	z_0 (m)	z_0 (in)
Gas Grill — Small (7.3 kW)	7.3	0.43	-0.09	n/a	-0.30	n/a
Gas Grill — Medium (11.7 kW)	11.7	0.51	0.01	0.4	-0.37	-14.6
Gas Grill — Large (17.6 kW)	17.6	0.58	0.14	5.5	-0.41	-16.1
Gas Grill — High-Output (23.4 kW)	23.4	0.65	0.26	10.2	-0.44	-17.3
Charcoal Kettle (4.4 kW)	4.4	0.56	-0.30	n/a	-0.47	n/a
Charcoal Kettle High (8.8 kW)	8.8	0.56	-0.13	n/a	-0.41	n/a
Charcoal Kamado (7.3 kW)	7.3	0.46	-0.05	n/a	-0.33	n/a
Wood-Fired (11.7 kW)	11.7	0.50	0.02	0.8	-0.36	-14.2
Wood-Fired Large (20.5 kW)	20.5	0.70	0.09	3.5	-0.48	-18.9
Pellet Smoker Low (2.3 kW)	2.3	0.45	-0.29	n/a	-0.38	n/a
Pellet Smoker Medium (5.3 kW)	5.3	0.45	-0.13	n/a	-0.32	n/a
Pellet Smoker High (8.8 kW)	8.8	0.45	0.01	0.4	-0.30	-11.8

Interpretation of Flame Height Results:

For most outdoor cooking sources, the Heskestad flame height L_f is negative or near-zero. This is a physically significant result: it means that for these heat release rates and source diameters, the mean visible flame height does not extend substantially above the cooking surface. The cooking surface diameter is large relative to the heat release rate; the fire is "fuel-controlled" and surface-dominated rather than producing a tall flame column.

When L_f is less than or equal to zero, the entire volume above the cooking surface is in McCaffrey's Zone 3 — the buoyant plume region. The Heskestad far-field plume correlations for centerline temperature, velocity, and mass flow are applicable immediately above the cooking surface (or, more precisely, above the thin thermal layer at the surface).

This is a fundamentally important finding: for the majority of common outdoor cooking configurations, there is no extended flame zone. The plume transitions to far-field self-similar behavior within the first few inches above the cooking surface. This contrasts with large pool fires or structural fires where flame heights of several meters are common. The distributed, low-intensity nature of outdoor cooking sources produces a plume that is already in the buoyancy-dominated regime at the heights where hoods are mounted.

Exceptions: The high-output gas grill (23.4 kW) and large wood-fired grill (20.5 kW) do produce short flame heights of 3 to 10 inches above the cooking surface. For these sources, the near-field to far-field transition occurs at a height of approximately L_f above the cooking surface, corresponding to approximately 10 inches or less. Even for these higher-output sources, all standard hood mounting heights (18" to 48") are well into the far-field regime.

Virtual Origin Interpretation:

The virtual origin z_0 is negative for all sources. This means the equivalent point source lies below the actual cooking surface. This is characteristic of distributed-area heat sources: the fire is spread over a wide area, and the plume from such a source is wider and slower at any given height than a plume from a point source of the same total heat release rate would be. The virtual origin correction accounts for this geometric effect.

In all subsequent calculations, the effective height for the Heskestad correlations is (z - z_0), where z is measured from the cooking surface. Since z_0 is negative, (z - z_0) is greater than z. This means the effective plume travel distance is greater than the physical mounting height, which is physically correct: the plume from a distributed source at height z behaves like a point-source plume that has traveled a greater distance and is therefore wider, slower, and cooler than a point-source plume at the same physical height.

3.3 Near-Field to Far-Field Transition Heights

Based on the flame height analysis and McCaffrey zone classification:

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Table 3.3: Transition Heights

Source Type	L_f (m)	Transition Height Above Cooking Surface	Classification
Gas Grill — Small	< 0	At cooking surface	Far-field at all hood heights
Gas Grill — Medium	~0	At cooking surface	Far-field at all hood heights
Gas Grill — Large	0.14 m (5.5")	~6 inches above grate	Far-field above ~6"
Gas Grill — High-Output	0.26 m (10.2")	~10 inches above grate	Far-field above ~10"
Charcoal Kettle	< 0	At cooking surface	Far-field at all hood heights
Wood-Fired Grill	~0	At cooking surface	Far-field at all hood heights
Wood-Fired Large	0.09 m (3.5")	~4 inches above grate	Far-field above ~4"
Pellet Smoker (all modes)	<= 0	At cooking surface	Far-field at all hood heights

Key Finding: For all standard outdoor cooking appliances operating at normal or maximum output, the **Near-Field Plume Region** is confined to the first 0 to 10 inches above the cooking surface. At all conventional hood mounting heights (18" to 48"), the plume has transitioned to self-similar far-field behavior and the Heskestad correlations apply without restriction.

This result simplifies subsequent ventilation analysis significantly. It is not necessary to account for combustion-zone phenomena or non-Boussinesq effects when analyzing plume conditions at hood mounting heights. However, the near-field behavior remains relevant for understanding hood thermal loading and radiant heat exposure at low mounting heights (addressed in RB-012).

3.4 Centerline Temperature Profiles

Applying the Heskestad centerline temperature correlation to representative cooking sources at standard hood mounting heights:

```
Delta_T_0 = 25.0 * Q_c^(2/3) * (z - z_0)^(-5/3)
```


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Table 3.4: Centerline Temperature Excess (Delta_T_0 in degrees C above ambient)

Height	Gas Small (Q_c=5.1 kW)	Gas Medium (Q_c=8.2 kW)	Gas Large (Q_c=12.3 kW)	Gas High (Q_c=16.4 kW)	Charcoal Kettle (Q_c=1.8 kW)	Wood-Fired (Q_c=7.6 kW)	Pellet Low (Q_c=1.5 kW)	Pellet High (Q_c=5.7 kW)
18" (0.46 m)	87	115	148	177	40	108	36	94
24" (0.61 m)	55	73	93	112	25	68	22	59
30" (0.76 m)	38	50	64	77	17	47	15	41
36" (0.91 m)	28	37	47	57	13	35	11	30
48" (1.22 m)	17	23	30	36	8	22	7	19

Calculation Methodology: For each source, (z - z_0) is computed using the virtual origins from Table 3.2. For example, for the Gas Grill — Medium at 24" (0.61 m): z - z_0 = 0.61 - (-0.37) = 0.98 m. Delta_T_0 = 25.0 * (8.2)^(2/3) * (0.98)^(-5/3) = 25.0 * 4.08 * 1.04 = 73 degrees C.

Physical Interpretation:

The temperature excess at the plume centerline drops rapidly with height. At 18 inches above a medium gas grill, the centerline is approximately 115 degrees C above ambient — a clearly detectable thermal plume. By 48 inches, this has decayed to only 23 degrees C above ambient. The z^(-5/3) decay is severe: doubling the height reduces the centerline temperature excess by a factor of approximately 3.2.

Charcoal grills and low-output pellet smokers generate modest temperature excess even at 18 inches, due to their low convective heat release rates. A charcoal kettle in glowing-ember mode produces only 40 degrees C excess at 18 inches. This does not mean the grill is producing less heat overall — it means the radiant fraction is high and the convective fraction driving the plume is low. The ventilation implication is that the charcoal plume is weaker and less well-defined, making it paradoxically harder to capture with a conventional hood despite lower total thermal output to the plume.

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3.5 Centerline Velocity Profiles

Applying the Heskestad centerline velocity correlation:

```
u_0 = 1.03 * Q_c^(1/3) * (z - z_0)^(-1/3)
```

Table 3.5: Centerline Velocity (u_0 in m/s)

Height	Gas Small (Q_c=5.1 kW)	Gas Medium (Q_c=8.2 kW)	Gas Large (Q_c=12.3 kW)	Gas High (Q_c=16.4 kW)	Charcoal Kettle (Q_c=1.8 kW)	Wood-Fired (Q_c=7.6 kW)	Pellet Low (Q_c=1.5 kW)	Pellet High (Q_c=5.7 kW)
18" (0.46 m)	2.01	2.30	2.60	2.83	1.45	2.25	1.38	2.06
24" (0.61 m)	1.85	2.12	2.39	2.60	1.33	2.07	1.27	1.90
30" (0.76 m)	1.74	1.99	2.25	2.44	1.25	1.94	1.19	1.78
36" (0.91 m)	1.64	1.88	2.12	2.31	1.18	1.84	1.13	1.68
48" (1.22 m)	1.49	1.71	1.93	2.10	1.07	1.67	1.02	1.53

Calculation Methodology: For the Gas Grill — Large at 30" (0.76 m): z - z_0 = 0.76 - (-0.41) = 1.17 m. u_0 = 1.03 * (12.3)^(1/3) * (1.17)^(-1/3) = 1.03 * 2.31 * 0.95 = 2.25 m/s.

Physical Interpretation:

Centerline velocity decays much more slowly than temperature. The z^(-1/3) power law means that doubling the height reduces velocity by only a factor of approximately 1.26. A medium gas grill produces a plume with centerline velocity of 2.30 m/s at 18 inches, decaying to 1.71 m/s at 48 inches — a reduction of only 26%.

Converting to more familiar units:

Height	Gas Medium (m/s)	Gas Medium (ft/min)	Gas Large (m/s)	Gas Large (ft/min)
18"	2.30	453	2.60	512
24"	2.12	417	2.39	470
30"	1.99	392	2.25	443
36"	1.88	370	2.12	417
48"	1.71	337	1.93	380

These velocities are significant in the context of ventilation design. Even at 48 inches above the source, a medium gas grill plume has a centerline velocity of 337 ft/min (1.71 m/s). For comparison, ASHRAE-recommended minimum face velocities for commercial kitchen hoods are 50 fpm (light duty), 80 fpm (medium duty), and 100 fpm (heavy duty). The plume centerline velocity exceeds these face velocity requirements at all mounting heights, which means that the challenge for outdoor hoods is not generating sufficient inward velocity to overcome the plume, but rather providing sufficient area coverage to intercept the full plume cross-section.

The charcoal kettle and low-output pellet smoker produce lower centerline velocities — approximately 1.0 to 1.5 m/s (200 to 295 ft/min) at standard hood heights — but these still exceed minimum capture velocity thresholds by a substantial margin.

3.6 Plume Diameter at Standard Hood Heights

The plume expands laterally with height due to entrainment. Using the Heskestad plume width formulation for the far-field regime:

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

The full plume diameter (to the Gaussian half-width points, encompassing approximately 95% of the buoyancy flux) is:

```
d_plume_95 = 2 * (1.6 * b_T) = 0.384 * (z - z_0)
```

For practical hood sizing, a factor of 2.0 to 2.4 times b_T is used to account for the full contaminant-carrying cross section plus margin for turbulent intermittency:

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

This additive term D_eff accounts for the finite source width.

Table 3.6: Plume Diameter for Hood Sizing (d_capture, in meters and inches)

Height	Gas Small (D=0.43m)	Gas Medium (D=0.51m)	Gas Large (D=0.58m)	Gas High (D=0.65m)	Charcoal Kettle (D=0.56m)	Wood-Fired (D=0.50m)	Pellet Smoker (D=0.45m)
18" (0.46 m)	0.79 m (31")	0.98 m (39")	1.05 m (41")	1.17 m (46")	1.00 m (39")	0.91 m (36")	0.85 m (33")
24" (0.61 m)	0.86 m (34")	1.06 m (42")	1.13 m (44")	1.26 m (50")	1.07 m (42")	0.97 m (38")	0.91 m (36")
30" (0.76 m)	0.94 m (37")	1.13 m (44")	1.20 m (47")	1.34 m (53")	1.14 m (45")	1.04 m (41")	0.97 m (38")
36" (0.91 m)	1.01 m (40")	1.20 m (47")	1.27 m (50")	1.41 m (56")	1.21 m (48")	1.11 m (44")	1.04 m (41")
48" (1.22 m)	1.16 m (46")	1.35 m (53")	1.42 m (56")	1.56 m (61")	1.36 m (54")	1.26 m (50")	1.19 m (47")

Physical Interpretation:

At 30 inches — a commonly specified mounting height — the plume from a medium gas grill has expanded to a capture diameter of approximately 44 inches. This means a hood must provide an **Effective Capture Area** spanning at least 44 inches in the grill's width dimension to intercept the full plume. Since the effective capture area is always less than the physical hood area (due to edge effects, velocity non-uniformity, and ambient air short-circuiting), the physical hood must be substantially larger than 44 inches.

At 48 inches, the same plume has expanded to 53 inches in capture diameter. The rapid increase in plume diameter with height is the primary geometric driver of the hood sizing problem. Each additional 6 inches of mounting height adds approximately 3 inches to the required capture diameter.

For large gas grills and high-output sources, the plume at 36 inches already exceeds 50 inches in diameter. This establishes a physical basis for minimum hood widths in the 54 to 66 inch range for these source types at this mounting height.

The charcoal kettle, despite having a lower total heat release rate, produces a capture diameter comparable to the medium gas grill because the charcoal grill's effective source diameter D_eff = 0.56 m contributes significantly to the initial plume width. The plume starts wider and grows at the same rate, compensating for the lower thermal driving force.

3.7 Plume Mass Flow Rate at Standard Hood Heights

The mass flow rate determines the minimum volumetric exhaust rate (CFM) the hood must provide. Using the Heskestad correlation for z > L_f:

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

Table 3.7: Plume Mass Flow Rate (kg/s) and Equivalent Volumetric Flow (CFM at plume temperature)

Height	Gas Medium (Q_c=8.2 kW) kg/s	Gas Medium CFM	Gas Large (Q_c=12.3 kW) kg/s	Gas Large CFM	Charcoal Kettle (Q_c=1.8 kW) kg/s	Charcoal CFM
18" (0.46 m)	0.043	78	0.050	93	0.031	55
24" (0.61 m)	0.066	119	0.076	140	0.047	84
30" (0.76 m)	0.093	168	0.107	197	0.067	119
36" (0.91 m)	0.124	223	0.143	262	0.090	159
48" (1.22 m)	0.196	352	0.226	413	0.143	252

Calculation Methodology: For Gas Medium at 30": m_dot_p = 0.071 * (8.2)^(1/3) * (0.76)^(5/3) + 0.0018 * 8.2 = 0.071 * 2.02 * 0.65 + 0.015 = 0.093 + 0.015 = 0.093 kg/s. Volumetric flow at plume temperature: V = m_dot / rho_plume. At Delta_T = 50 K above ambient 293 K, rho_plume

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approximately equals 1.2 * 293/343 = 1.02 kg/m^3. V = 0.093/1.02 = 0.091 m^3/s = 168 CFM (accounting for temperature-adjusted density using local plume conditions, averaged across the cross section — note the effective average is lower than centerline values).

Critical Interpretation:

These mass flow rates represent the minimum amount of air that flows through the **Plume Interception Plane** at each height. A hood that exhausts less than this flow rate cannot physically capture the entire plume. In practice, the hood must exhaust substantially more than these values because:

1. The hood draws in ambient air from all sides, not just plume gas. The entrained ambient air constitutes a large fraction of total exhaust flow.
2. In an outdoor environment without enclosure walls, there is no pressure-assisted recirculation of escaped plume back toward the hood. Any plume flow not captured on the first pass is permanently lost.
3. Turbulent fluctuations and wind perturbations require margin above the mean plume flow rate.

These plume flow rates should be understood as the absolute physical minimum. Practical outdoor hood exhaust rates are addressed in RB-008 and are typically 3 to 6 times the values shown here.

The z^(5/3) dependence of mass flow rate on height is the most consequential scaling relationship for ventilation design. Increasing mounting height from 24" to 48" approximately triples the plume mass flow rate (from 119 CFM to 352 CFM for the medium gas grill). This nonlinear growth in the volume of air that must be captured and exhausted is the fundamental physical reason that hood mounting height must be minimized.

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4. 4. Implications for Outdoor BBQ Ventilation

4.1 Mounting Height Is the Dominant Design Variable

The calculations in Section 3 demonstrate that mounting height affects every plume parameter relevant to capture:

- **Centerline temperature excess** drops as (z - z_0)^(-5/3) — reducing by a factor of approximately 3.2 when height doubles
- **Centerline velocity** drops as (z - z_0)^(-1/3) — reducing by approximately 26% when height doubles

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- **Plume diameter** grows linearly with height — adding approximately 3 inches of capture diameter per 6 inches of height
- **Mass flow rate** grows as z^(5/3) — approximately tripling when height doubles

Of these, the mass flow rate scaling is the most consequential for hood specification. A hood mounted at 48 inches must exhaust approximately three times the air volume as one mounted at 24 inches to capture the same source plume. This directly drives blower size, energy consumption, noise generation, and duct sizing.

The implication is clear: for outdoor installations where wind, open boundaries, and absence of enclosure walls already degrade capture performance, mounting height should be the minimum consistent with operational clearance, head clearance, and fire safety codes. Every unnecessary inch of mounting height compounds the ventilation challenge.

4.2 Source Type Affects Plume Character, Not Just Magnitude

The heat release rate alone does not determine plume behavior at the **Plume Interception Plane**. The convective fraction (chi_c), the effective source diameter (D_eff), and the combustion mode all affect the plume profile at hood height.

Gas grills produce the strongest, most well-defined plumes per unit of total heat release because their high convective fraction (0.70) efficiently converts combustion energy into buoyant driving force. The plume is coherent, thermally strong, and relatively narrow for a given heat release rate.

Charcoal grills produce plumes that are weaker than their total BTU rating suggests, because the dominant radiant-heat mode directs energy to the food and surroundings rather than into the rising gas column. A charcoal grill rated at 30,000 BTU/hr produces a plume comparable to a gas grill of only approximately 12,000-15,000 BTU/hr in convective terms. However, the charcoal grill's cooking surface (the entire coal bed) is typically wider than the burner array of a comparably rated gas grill, so the plume starts wider. The combination of lower velocity and wider initial diameter makes the charcoal plume more difficult to contain within the **Capture Envelope** at elevated mounting heights.

Wood-fired grills produce plumes intermediate between gas and charcoal. The convective fraction is moderate (0.65) and the source diameter can be large (especially for Argentine-style or multi-log configurations). The distinguishing characteristic of wood-fired plumes is their intermittent and irregular character: shifting fuel beds, fluctuating flame geometry, and wind-induced draft variations produce a plume with higher turbulence intensity and greater instantaneous displacement than gas grill plumes. This increases the margin required between calculated plume diameter and hood overhang.

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Pellet smokers present a unique ventilation challenge. In low-temperature smoking mode, the convective heat release rate is so low (1.5 kW) that the resulting plume is weak, slow (approximately 1.0-1.4 m/s centerline velocity), and easily disrupted by ambient wind. The plume contains high concentrations of fine smoke particulates that are the desired product of the smoking process but represent a challenging contaminant for capture. At high-temperature grilling mode, the pellet smoker plume approaches that of a small gas grill and is more readily captured.

4.3 The Charcoal Paradox

The analysis reveals a paradox that is commonly misunderstood in outdoor ventilation practice:

Charcoal grills often produce more smoke, more grease aerosol, and more combustion byproducts per unit of cooking time than gas grills. They are commonly perceived as "harder to ventilate." However, the physics shows that the charcoal grill produces a *weaker* buoyant plume (lower centerline velocity, lower temperature excess) because the dominant radiant-heat mode reduces the convective fraction driving plume buoyancy.

The difficulty with charcoal ventilation is not that the plume is too strong for the hood — it is that the plume is too weak and diffuse. The contaminants are there, but the thermal driving force to lift them coherently into the hood is diminished. The contaminant-laden plume meanders and disperses more readily, escaping the **Capture Envelope** at lower wind speeds and greater distances from centerline.

This has a specific design implication: for charcoal grills, the hood should be mounted as low as possible (to intercept the plume while it still has meaningful velocity) and the overhang should be generous (to capture the wider, more diffuse plume cross-section). Increasing exhaust CFM alone is less effective for charcoal than for gas because the fundamental issue is geometric — the contaminants are spread across a wider, less coherent plume.

4.4 Why All Hood Heights Are in the Far-Field

The flame height analysis confirms that for all standard outdoor cooking appliances, the plume at hood mounting heights is in the buoyant plume region (McCaffrey Zone 3) with well-established self-similar Gaussian profiles. This has important practical implications:

1. The same set of Heskestad correlations applies to all source types at all standard mounting heights. There is no need for separate near-field models or combustion-zone corrections when analyzing hood performance.
2. The plume at hood height is dominated by entrained ambient air, not by combustion gases. Even at 18 inches above a large gas grill, the plume mass flow is approximately 80% entrained ambient air. The captured fluid is mostly clean air carrying diluted contaminants.

3. The Gaussian profile assumption is valid, meaning the contaminant concentration (smoke, grease, combustion products) is highest at the plume centerline and falls off radially following the same Gaussian distribution as temperature and velocity. This justifies the practice of centering the hood over the cooking surface for optimal capture.

4.5 The Entrainment Tax

Every inch of mounting height imposes what can be termed an "entrainment tax" — the progressive addition of ambient air into the plume through the **Entrainment Zone** dilutes the contaminant concentration but increases the total volume that must be captured. This entrainment is governed by the Morton-Taylor-Turner mechanism and cannot be eliminated by hood design; it is a fundamental property of turbulent buoyant plumes.

At 48 inches above a medium gas grill, the plume mass flow rate is 352 CFM. Of this, only approximately 15 CFM originated at the cooking surface; the remaining approximately 337 CFM is ambient air entrained during the plume's rise. The hood must capture and exhaust all 352 CFM (plus additional ambient air that enters the hood from beyond the plume boundary) to achieve complete capture.

This physical reality means that outdoor hoods must be designed as "plume interceptors" rather than "contaminant extractors." The hood does not selectively extract contaminants from the plume; it captures the entire plume cross-section, contaminants and entrained air together. The hood's job is purely geometric: to have sufficient **Effective Capture Area** at the **Plume Interception Plane** to encompass the full plume diameter, and sufficient exhaust rate to ingest the total plume mass flow.

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5. 5. Knowledge Gaps or Opportunities

5.1 Well-Established Knowledge

The following aspects of outdoor cooking plume behavior are well-established in the fire science and fluid dynamics literature:

- The MTT entrainment model and Heskestad plume correlations are validated against extensive fire test data and are accepted as standard engineering tools
- The z^(-1/3) velocity decay and z^(-5/3) temperature decay relationships are robust and well-confirmed for axisymmetric buoyant plumes above flame height
- The linear growth of plume radius with height is well-established for the far-field

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- The mass flow rate scaling with $z^{(5/3)}$ is a direct consequence of the conservation equations and is not subject to significant uncertainty
- McCaffrey's three-zone classification is the accepted framework for fire plume structure

5.2 Commonly Misunderstood

The following aspects are commonly misunderstood or misapplied in the outdoor cooking ventilation context:

1. **BTU rating as a proxy for plume strength.** The total BTU rating of a cooking appliance is not the correct input for plume calculations. The convective heat release rate (Q_c), which can be as low as 40% of total BTU for charcoal grills, is the parameter that governs plume behavior. Using total BTU without convective correction overestimates the plume strength of charcoal and underestimates the relative difficulty of capturing its more diffuse contaminant output.

2. **Indoor hood CFM as outdoor guidance.** Indoor kitchen ventilation operates in an enclosed environment where walls redirect escaped plume, ceiling jet effects enhance capture, and room pressurization assists flow toward the exhaust. None of these mechanisms exist outdoors. Indoor CFM specifications are not transferable to outdoor installations without explicit correction for the open-boundary condition (addressed in RB-004).

3. **Mounting height as a linear variable.** Because plume diameter grows linearly with height but mass flow rate grows as $z^{(5/3)}$, the penalty for increasing mounting height is much more severe than commonly assumed. A linear interpolation between hood specifications at different heights substantially underestimates the required exhaust rate at greater heights.

4. **Plume velocity as the capture challenge.** The plume centerline velocities (1-3 m/s) substantially exceed minimum capture velocities specified for commercial kitchen hoods (0.25-0.5 m/s). The capture challenge for outdoor cooking is not velocity but geometry: the plume is wide, the hood has no confining walls, and wind displaces the plume laterally. Specifying higher capture velocities (higher CFM) does not solve a geometric mismatch between plume diameter and **Effective Capture Area**.

5.3 Missing or Insufficient in Current Literature

1. **No published plume characterization data specific to outdoor cooking sources.** The Heskestad correlations and MTT theory are derived from fire plume experiments using pool fires, gas burners, and solid fuel cribs. While the physics is transferable, no published experimental data

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validates these correlations specifically for the heat release rates, source geometries, and fuel types characteristic of outdoor barbecue cooking. The convective fractions used in this paper are estimated from general combustion science, not from calorimetry of operating barbecues.

2. **No standard test method for outdoor cooking plume characterization.** ASTM E3087 defines a capture efficiency test for residential range hoods, but it is designed for indoor cooktop scenarios with specific cooking loads. No equivalent standard exists for outdoor cooking sources.

3. **Convective fraction uncertainty for charcoal.** The convective fraction for charcoal grills is the most uncertain parameter in this analysis. Published values for charcoal combustion radiative fraction range from 0.25 to 0.55 depending on coal bed maturity, airflow, fuel type (briquettes vs. lump), and whether active flames are present. This introduces uncertainty of approximately plus or minus 30% in the calculated plume velocities and temperatures for charcoal sources.

4. **Effect of food and cookware on plume.** The plume from an operating barbecue is not a pure buoyant plume from a clean heat source. Food, drippings, and cookware modify the thermal and contaminant character of the plume. Fat dripping onto hot surfaces produces secondary plumes with transient high heat release rates. These intermittent events are not captured by steady-state plume correlations and may produce momentary plume conditions that exceed the **Capture Envelope** of a hood sized for steady-state operation.

5. **Outdoor ambient wind interaction with plume.** This paper characterizes the undisturbed buoyant plume in still-air conditions. The interaction of ambient wind with the plume — deflection, enhanced entrainment, disruption — is addressed in RB-006. However, the coupling between wind effects and the source-specific plume parameters characterized here has not been experimentally studied for outdoor cooking scenarios.

6. **Absence of validated outdoor hood sizing methodology.** No published methodology exists for sizing outdoor barbecue hoods based on plume physics. Current practice relies on indoor ventilation rules of thumb, manufacturer experience, and empirical adjustment. The plume characterization in this paper provides the physical foundation for developing such a methodology (addressed in RB-008).

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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: Buoyant Cooking Plume Profile for Gas Grill (Diagram Type 1)

Purpose: Illustrate the full structure of the **Buoyant Cooking Plume** from a medium gas grill (Q_c = 8.2 kW, D_{eff} = 0.51 m).

Content:

- Cooking surface shown as a horizontal bar at z = 0, width = 0.51 m
- **Near-Field Plume Region** shaded in darker warm gradient, extending from z = 0 to approximately z = 0.05 m (2 inches), labeled with note "L_f approximately 0; transition to far-field is immediate for this source"
- Far-field plume body in lighter warm gradient (amber to pale yellow), expanding linearly from D_{eff} = 0.51 m at z = 0 to $d_{capture}$ = 1.35 m at z = 1.22 m (48 inches)
- Plume centerline shown as dashed vertical line
- Plume boundary edges at half-angle of approximately 7 degrees from centerline
- Entrainment arrows (gray, horizontal, pointing inward) at heights of 0.25 m, 0.50 m, 0.75 m, and 1.0 m, with arrow length proportional to local entrainment velocity ($U_e = \alpha * u_0$)
- Centerline velocity annotations at 18", 24", 30", 36", 48" showing values from Table 3.5
- Centerline temperature annotations at the same heights showing values from Table 3.4
- Scale bar at left showing height in both inches and meters
- "**Velocity Decay**: $u_0 \sim z^{(-1/3)}$" annotation along centerline
- "**Entrainment Zone**" label at plume boundary with entrainment arrows
- Figure caption: "Figure 1.1: Buoyant Cooking Plume profile for a medium gas grill (Q_c = 8.2 kW). The plume transitions to self-similar far-field behavior immediately above the cooking surface (L_f approximately 0). Centerline velocity and temperature values are calculated using Heskestad plume correlations."

Diagram 6.2: Entrainment and Velocity Decay Comparison Across Source Types (Diagram Type 2)

Purpose: Show the quantitative differences in **Velocity Decay** and plume diameter expansion between a gas grill, charcoal grill, and pellet smoker.

Content:

- Three plumes shown side-by-side or overlaid on the same vertical axis (z from 0 to 1.22 m)
- Gas grill (Q_c = 12.3 kW): strongest plume, narrowest for its heat input, highest velocities

- Charcoal kettle (Q_c = 1.8 kW): weakest plume, but starts wide due to large D_{eff}
- Pellet smoker low (Q_c = 1.5 kW): weakest plume overall, narrow source
- Side panel on right showing velocity decay curves (u_0 vs z) for all three sources
- Velocity decay exponent notation: "$u_0 \sim Q_c^{1/3} * z^{-1/3}$"
- Temperature decay exponent notation: "$\Delta T \sim Q_c^{2/3} * z^{-5/3}$"
- Entrainment arrows at multiple heights, with arrow length reflecting $\alpha * u_0$ at each height (longer arrows for stronger plumes)
- Annotation comparing Q_c values: "Same BTU output does not produce same plume. Convective fraction determines plume strength."
- Figure caption: "Figure 2.1: Comparative Velocity Decay and plume growth for three outdoor cooking sources. The gas grill produces the strongest, most coherent plume per unit total heat release due to its high convective fraction. The charcoal grill produces a weaker, wider plume despite substantial total BTU output."

Diagram 6.3: Hood-Plume Geometry at Multiple Mounting Heights (Diagram Type 3)

Purpose: Show how the relationship between plume diameter and hood geometry changes with mounting height.

Content:

- A single medium gas grill source (Q_c = 8.2 kW) shown at center bottom
- Plume expanding upward with labeled diameter at 24", 30", 36", and 48"
- Hood outlines shown at each height, drawn to scale (e.g., 48-inch hood width)
- At 24": plume diameter (42") fits within hood (48") with margin — label "Capture Success"
- At 36": plume diameter (47") approaches hood width — label "Marginal Capture"
- At 48": plume diameter (53") exceeds hood width — label "Capture Failure: **Missed Plume Region** extends beyond hood boundaries"
- **Plume Interception Plane** shown as horizontal dashed line at each hood height
- **Effective Capture Area** highlighted in blue on the hood faces where it is smaller than total hood area
- Dimension lines showing plume diameter vs. hood width at each height

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- Figure caption: "Figure 3.1: Hood-plume geometric relationship at four mounting heights for a medium gas grill (Q_c = 8.2 kW) with a 48-inch hood. At 24 inches, the plume is fully captured. At 48 inches, the plume diameter exceeds the hood width and the Missed Plume Region becomes significant."

Diagram 6.4: Convective Fraction Effect on Plume Strength (New — Propose for inclusion in Diagram Standard)

Purpose: Illustrate why two sources with identical total BTU output produce different plumes when their convective fractions differ.

Content:

- Two side-by-side plume profiles:
  - Left: Gas grill at 30,000 BTU/hr (Q_total = 8.8 kW, chi_c = 0.70, Q_c = 6.2 kW)
  - Right: Charcoal grill at 30,000 BTU/hr (Q_total = 8.8 kW, chi_c = 0.40, Q_c = 3.5 kW)
- Gas plume: narrower, taller, faster, more concentrated (darker shading at centerline)
- Charcoal plume: wider at base (larger D_eff), slower, more diffuse (lighter shading)
- Radiation arrows emanating laterally from charcoal grill surface (showing where the "missing" convective energy goes)
- Velocity annotations at 30" height: gas = 2.0 m/s, charcoal = 1.6 m/s
- Temperature annotations at 30" height: gas = 49 degrees C above ambient, charcoal = 22 degrees C above ambient
- Label: "Same total BTU. Different plume. The convective fraction determines how much energy enters the Buoyant Cooking Plume."
- Figure caption: "Figure 4.1: Effect of convective fraction on plume strength. A gas grill and charcoal grill with identical total heat release rates (30,000 BTU/hr) produce substantially different Buoyant Cooking Plumes because the charcoal grill's dominant radiant-heat mode reduces the convective driving force of the plume."

Diagram 6.5: Mass Flow Rate Growth with Height (New — Quantitative Chart)

Purpose: Show the nonlinear (z^(5/3)) growth of plume mass flow rate with mounting height, emphasizing the "entrainment tax."

Content:

- X-axis: mounting height (18" to 60")

- Y-axis: plume mass flow rate (CFM)
- Curves for: Gas Small, Gas Medium, Gas Large, Charcoal Kettle, Pellet Smoker High
- Annotation showing the z^(5/3) relationship: "Mass flow increases approximately 3x when height doubles"
- Highlight region from 30" to 48" with annotation: "This 18-inch increase in height approximately doubles the required exhaust flow"
- Dashed horizontal lines showing common hood CFM ratings (e.g., 600 CFM, 900 CFM, 1200 CFM) for context
- Note: "These values represent the plume mass flow only. Total hood exhaust must exceed these values to account for ambient air ingestion and wind margin."
- Figure caption: "Figure 5.1: Plume mass flow rate as a function of mounting height for representative outdoor cooking sources. The z^(5/3) growth rate imposes a substantial nonlinear penalty on hood exhaust requirements as mounting height increases."

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7. Appendix A: Standard Ambient Conditions Used in All Calculations

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)	alpha	0.11	dimensionless

These values represent standard sea-level conditions. At elevated sites (e.g., Denver at 1,600 m elevation), ambient density is approximately 17% lower and plume buoyancy effects are correspondingly altered. Altitude corrections are not addressed in this paper.

8. Appendix B: 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
Temperature	Delta_T (K)	Delta_T (degrees C) = Delta_T (K); Delta_T (degrees F) = 1.8 * Delta_T (K)

9. Appendix C: Summary of Key Correlations Used

All correlations are from Heskestad, G., "Fire Plumes, Flame Height, and Air Entrainment," SFPE Handbook of Fire Protection Engineering, 5th Edition, Chapter 13, Springer, 2016; and Morton, B.R., Taylor, G.I., and Turner, J.S., "Turbulent gravitational convection from maintained and instantaneous sources," Proceedings of the Royal Society A, Vol. 234, pp. 1-23, 1956.

Parameter	Formula	Domain of Validity
Flame height	L_f = 0.235 * Q_total^(2/5) - 1.02 * D	Q in kW, D in m
Virtual origin	z_0 = 0.083 * Q_total^(2/5) - 1.02 * D	Q in kW, D in m
Centerline temperature rise	Delta_T_0 = 25.0 * Q_c^(2/3) * (z-z_0)^(-5/3)	z > L_f; standard ambient
Centerline velocity	u_0 = 1.03 * Q_c^(1/3) * (z-z_0)^(-1/3)	z > L_f; standard ambient
Mass flow (above flames)	m_dot = 0.071 * Q_c^(1/3) * z^(5/3) + 0.0018 * Q_c	z > L_f; kg/s, kW, m
Mass flow (below flames)	m_dot = 0.032 * Q_c^(3/5) * z	z < L_f; kg/s, kW, m
Plume width (Gaussian 1/e)	b_T = 0.12 * (z - z_0)	z > L_f; meters
Plume radius (MTT)	b = (6/5) * alpha * z	Far-field; alpha approximately 0.11

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10. References

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