Most of the Smoke Is Not What Burned but Air the Plume Pulled In, So What Sets the Volume of Smoke Is the Ceiling Height

— A 1000 kW fire burns only 0.076923 kg/s of fuel, yet the plume at a height of 5 m carries 9.216677 kg/s — the separator is whether the volume of smoke is set by the fuel or by the ceiling height — [Paper 728]

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— *From thinking to syncing.* —

Abstract

The smoke in a fire is taken to be what burned. Counted by mass, most of it never burned at all.What burned and what became smoke are set side by side in the same units.No new theorem or law is claimed. First, the mass burning is small——even at 1000 kW it is 0.076923 kg/s (Section 2). **Second, and this is the core. The smoke is 119.816801 times that——the plume at 5 m carries 9.216677 kg/s, of which 0.991654 is entrained air** (Section 2). **Third, entrainment depends strongly on height——at the 5/3 power, so doubling the ceiling gives 3.174802** (Section 3). **Fourth, the size of the fire matters only weakly——at the 1/3 power, so quadrupling the output gives merely 1.587401** (Section 3). **Fifth, so the smoke descends quickly——in a room of 400 m² with a 5 m ceiling it reaches head height in 80.188721 seconds** (Section 3). **Sixth, the separator is whether the volume of smoke is set by the fuel or by the ceiling height——reduce the fuel and a high ceiling still gives more smoke** (Section 4). **Keywords**: fire plume, entrainment, smoke layer descent, mass flow, ceiling height, where smoke comes from.

Scope of this paper (scope note): **No new theorem or law is claimed——plume entrainment, smoke layer descent and the mass flow expression for a fire plume are all standard (Zukoski 1981, Drysdale 1985).No precision is claimed for representative values——the entrainment coefficient of 0.071, a convective fraction of 0.7, a heat of combustion of 13 MJ/kg and a smoke temperature of 300 °C are all order-of-magnitude values.Fire growth is not included——growth of the output with time is not treated; a steady output is used.Openings are not treated——neither smoke extraction nor outflow through doors and windows is treated; the room is counted as closed.Evacuation is not discussed——visibility, toxicity and human movement are not treated.Two layers are assumed——an upper smoke layer and a lower clear layer, with mixing at the interface not treated.Relation to earlier papers**: **Paper 577 showed that fire grows as the square of time, so the weight of the same minute's delay changes——there the growth of the fire was the subject, on the side of time. Here we count the smoke that the same fire makes. The speed of growth, and the volume the grown fire fills.**What is added is **putting the ratio of smoke to fuel at 119.816801**, **showing 0.991654 of the smoke to be air**, **setting the 5/3 power of height beside the 1/3 power of output**, **deriving a descent time of 80.188721 seconds**, and **placing the separator on fuel against ceiling height**.

1. Notation and the Question

Setting: **a plume forms above a fire and rises while entraining the surrounding air. Its mass flow at height z is written in the $1/3$ power of the convective output and the $5/3$ power of the height.**

$$\dot{m} = C\,\dot{Q}_c^{1/3} z^{5/3}, \qquad \dot{m}_{\text{fuel}} = \frac{\dot{Q}}{\Delta H_c}, \qquad t_{\text{descent}} = \frac{V_{\text{above}}}{\dot{m}/\rho_{\text{smoke}}}$$

$C = 0.071$, a convective fraction of 0.7 of the total output, and a heat of combustion of 13 MJ/kg are taken as representative.

Question: **what is smoke made of?**

2. The Smoke Is More Than a Hundred Times What Burned

Computation 2.1: **for a 1000 kW fire, the plume mass flow was derived at each height.**

height	plume mass flow	times the mass burning
2 m	2.001433 kg/s	26.018627
5 m	9.216677 kg/s	119.816801
10 m	29.261126 kg/s	380.394633
20 m	92.898283 kg/s	1207.677682

> **Observation 2.2**
>
> **this is the core: the mass burning is only 0.076923 kg/s.The smoke at 5 m is 119.816801 times that, and 0.991654 of it is entrained air——reading smoke as “what burned” misjudges the quantity by two orders.**

> **Observation 2.3**
>
> **so “keep combustible things out” is not enough.What sets the volume of smoke is not the fuel but the height the plume rises through——the same fire under a higher ceiling makes more smoke.**

3. Height Matters Strongly, the Fire’s Size Weakly

Computation 3.1: **the two exponents were compared.**

quantity varied	exponent	factor on doubling or quadrupling
height	5/3	3.174802 (doubled)
output	1/3	1.587401 (quadrupled)

> **Observation 3.2**
>
> **doubling the height beats quadrupling the output.3.174802 against 1.587401——ceiling height is fixed by the design of the building, so half the smoke quantity is settled before any fire starts.**

Computation 3.3: **with smoke at 300 °C (density 0.616028 kg/m³), the time for the layer to descend to head height at 2 m in a room of 400 m² with a 5 m ceiling was derived.**

quantity	value
volume flow	**14.961450** m³/s
volume to be filled	**1200** m³
descent time	**80.188721** s (**1.336479** min)
mass burned in that time	**6.168363** kg
air turned to smoke in that time	**732.905178** kg

> **Observation 3.4**
>
> **head height is reached in a minute and a half.In that time 6.168363 kg burned while 732.905178 kg of air became smoke——during the interval in which the fire still looks small, the smoke has filled the room.**

> **Observation 3.5**
>
> **hotter smoke occupies more volume.Smoke at 300 °C is lighter than room air, so the same mass takes more volume——the descent is therefore set by volume, not by mass.**

4. The Separator

> **Observation 4.1**
>
> **the separator is whether the volume of smoke is set by the fuel or by the ceiling height.Reduce the fuel and a high ceiling still gives more smoke——reading smoke as “where the burned matter went” or as “where the entrained air went” changes what one would alter to reduce it.**

Observation 4.2

beside Paper 577.Paper 577 showed that fire grows as the square of time, so the weight of the same minute's delay changes——there time was the subject. Here it is quantity, and the quantity does not come from the fuel. The speed of growth, and the volume filled.

Observation 4.3

what is not said.Fire growth, smoke extraction and evacuation are not treated, and four representative values are held fixed——what is shown is where the mass of the smoke comes from, and which of two exponents is larger.

5. Roll Call and Closing

1. **0.076923 kg/s burning** (Computation 2.1): **at 1000 kW.**
2. **9.216677 kg/s at 5 m** (Computation 2.1): **the plume.**
3. **a factor of 119.816801** (Observation 2.2): **the core.**
4. **0.991654 of it is air** (Observation 2.2): **it never burned.**
5. **1207.677682 at 20 m** (Computation 2.1): **more still.**
6. **doubling height gives 3.174802** (Computation 3.1): **the 5/3 power.**
7. **quadrupling output gives 1.587401** (Computation 3.1): **the 1/3 power.**
8. **descent in 80.188721 s** (Computation 3.3): **a minute and a half.**
9. **6.168363 kg burned** (Computation 3.3): **against 732.905178 kg of air.**
10. **fuel or ceiling height** (Observation 4.1): **the separator; Paper 577.**

Closing: **Most of the smoke is not what burned but air the plume pulled in, so what sets the volume of smoke is the ceiling height.A 1000 kW fire burns only 0.076923 kg/s, yet the plume at 5 m carries 9.216677 kg/s, a factor of 119.816801, of which 0.991654 is entrained air——reading smoke as "what burned" misjudges the quantity by two orders.And entrainment goes as the 5/3 power of height, so doubling the ceiling gives 3.174802, while it goes only as the 1/3 power of output, so quadrupling that gives merely 1.587401——ceiling height is fixed by the design of the building, so half the smoke quantity is settled before any fire starts.In a room of 400 m² with a 5 m ceiling, smoke at 300 °C and a density of 0.616028 kg/m³ gives a volume flow of 14.961450 m³/s, so the layer reaches head height at 2 m in 80.188721 seconds——in that time 6.168363 kg burned while 732.905178 kg of air became smoke: during the**

interval in which the fire still looks small, the smoke has filled the room.The separator is whether the volume of smoke is set by the fuel or by the ceiling height——reduce the fuel and a high ceiling still gives more smoke.Placed among the earlier papers——Paper 577 treated the side of time; here it is quantity, and the quantity does not come from the fuel.To be honest——fire growth, smoke extraction and evacuation are not treated, and four representative values are held fixed.

References

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