Biomass Combustor Design

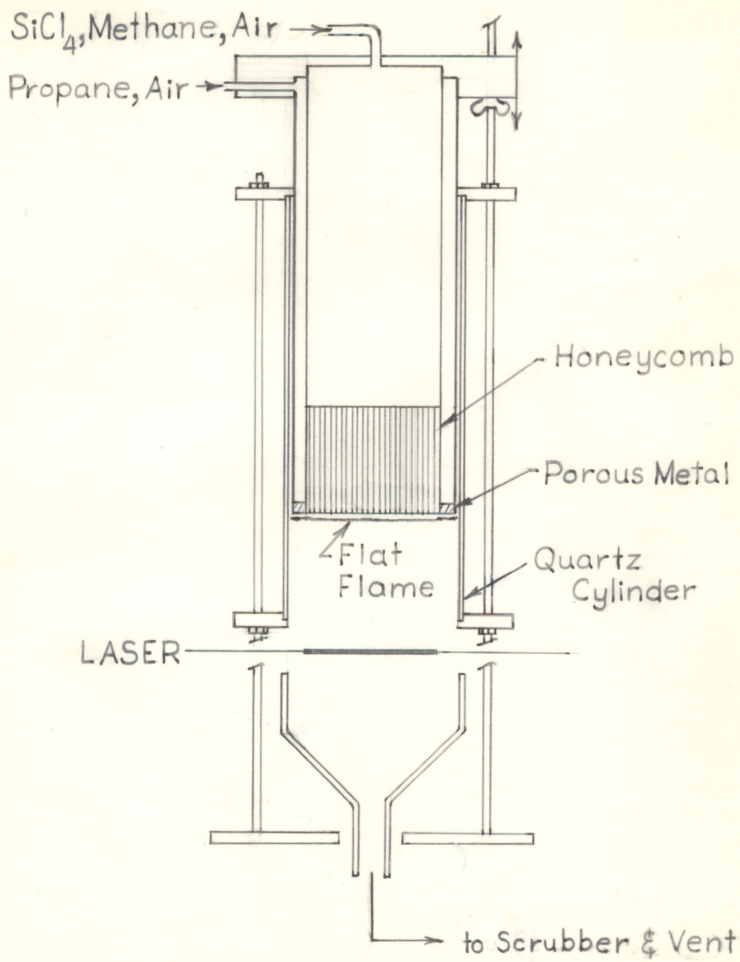
Alliance for Green Heat BNL Workshop

(Gael Ulrich 4 November 2014)

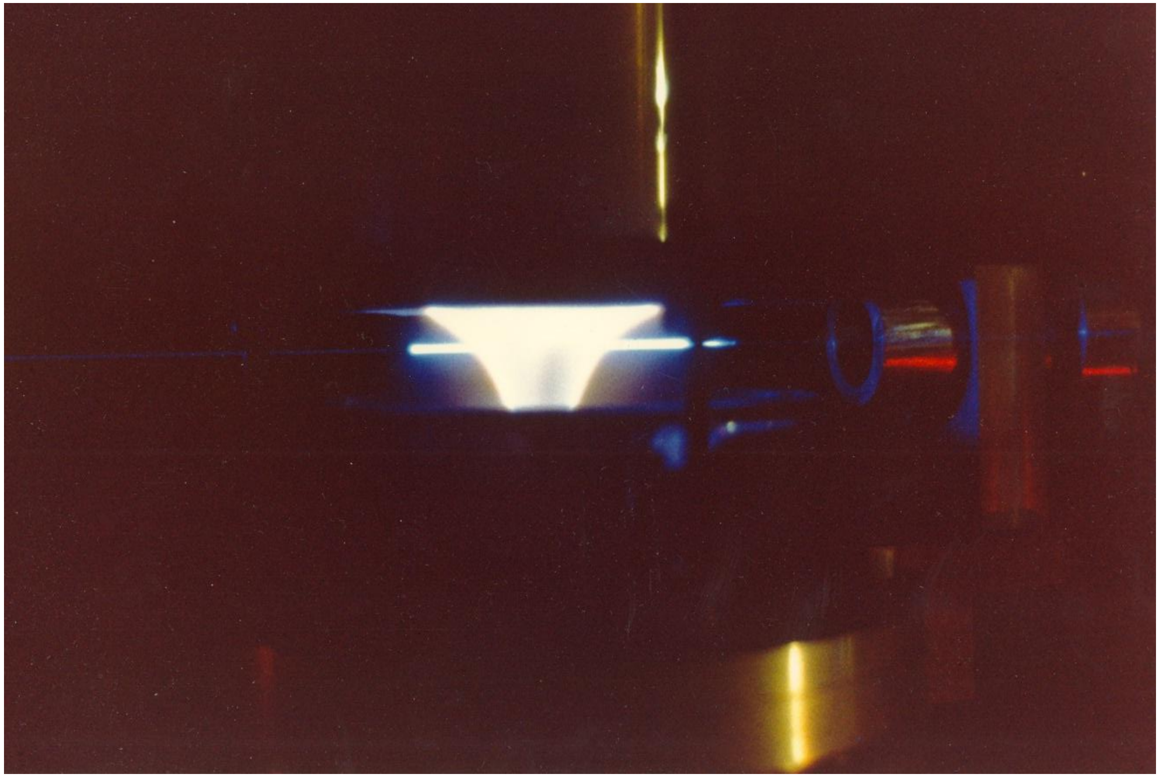
Smoke Particle Formation Fundamentals

Sophisticated Smoke (white soot)
Valuable Smoke (carbon black)

Combustion Science and Technology Applied to the Design of a Particular Biomass Combustor

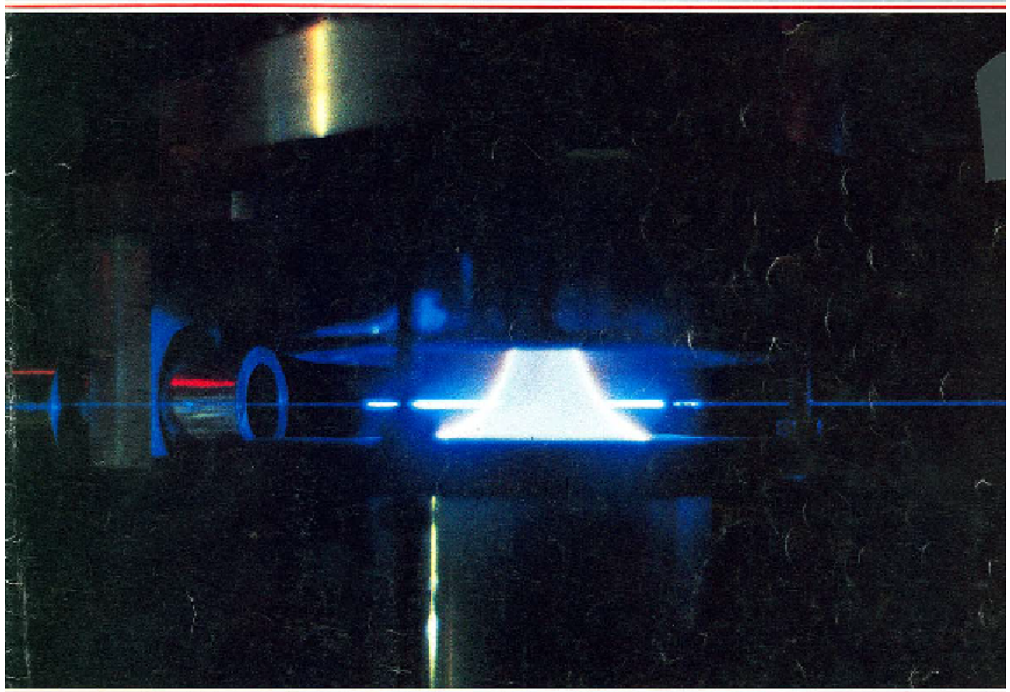


$SiCl_4$, Methane, Air
Propane, Air
Honeycomb
Porous Metal
Flat Flame
Quartz Cylinder
LASER
to Scrubber & Vent



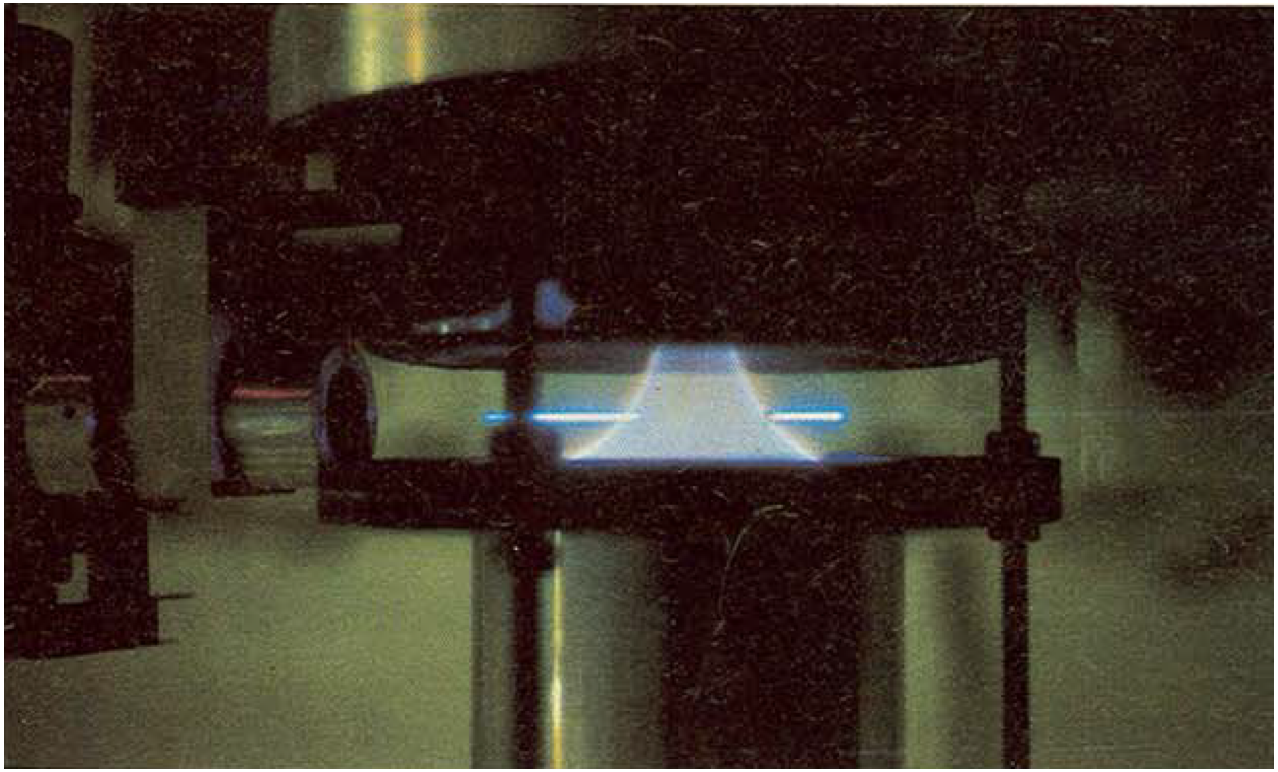
PRELIMINARY PROGRAM
1984 International Chemical Congress of
Pacific Basin Societies—Honolulu Page 35

AUGUST 6, 1984
CHEMICAL & ENGINEERING
NEWS

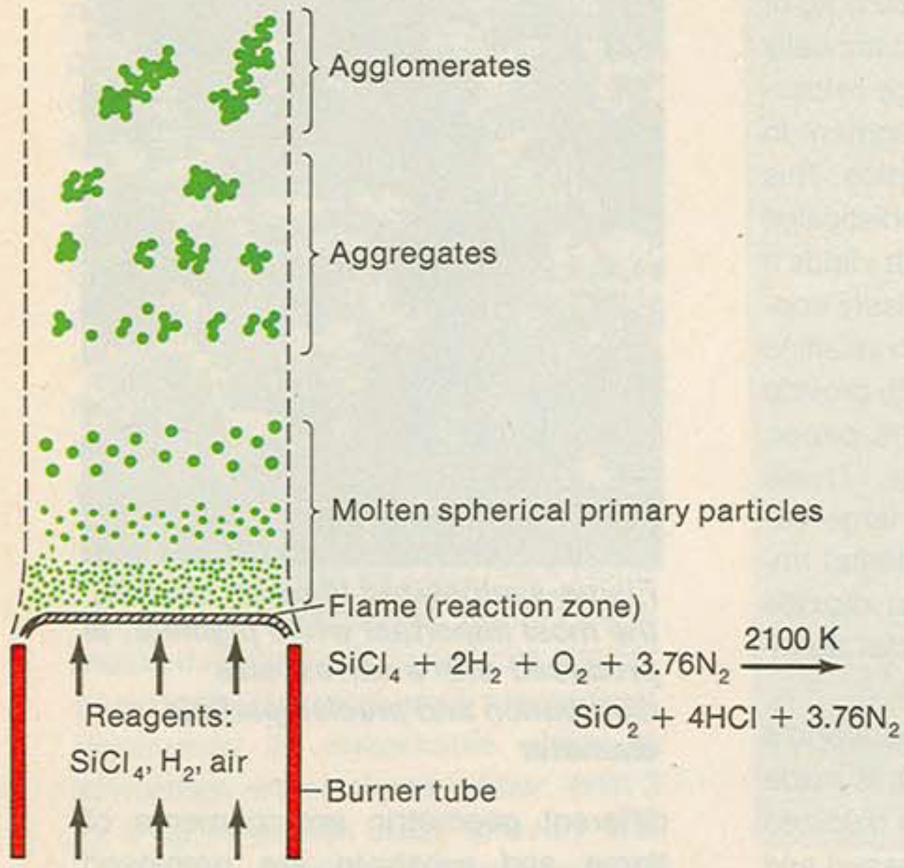


Flame-Generated Fine Particles

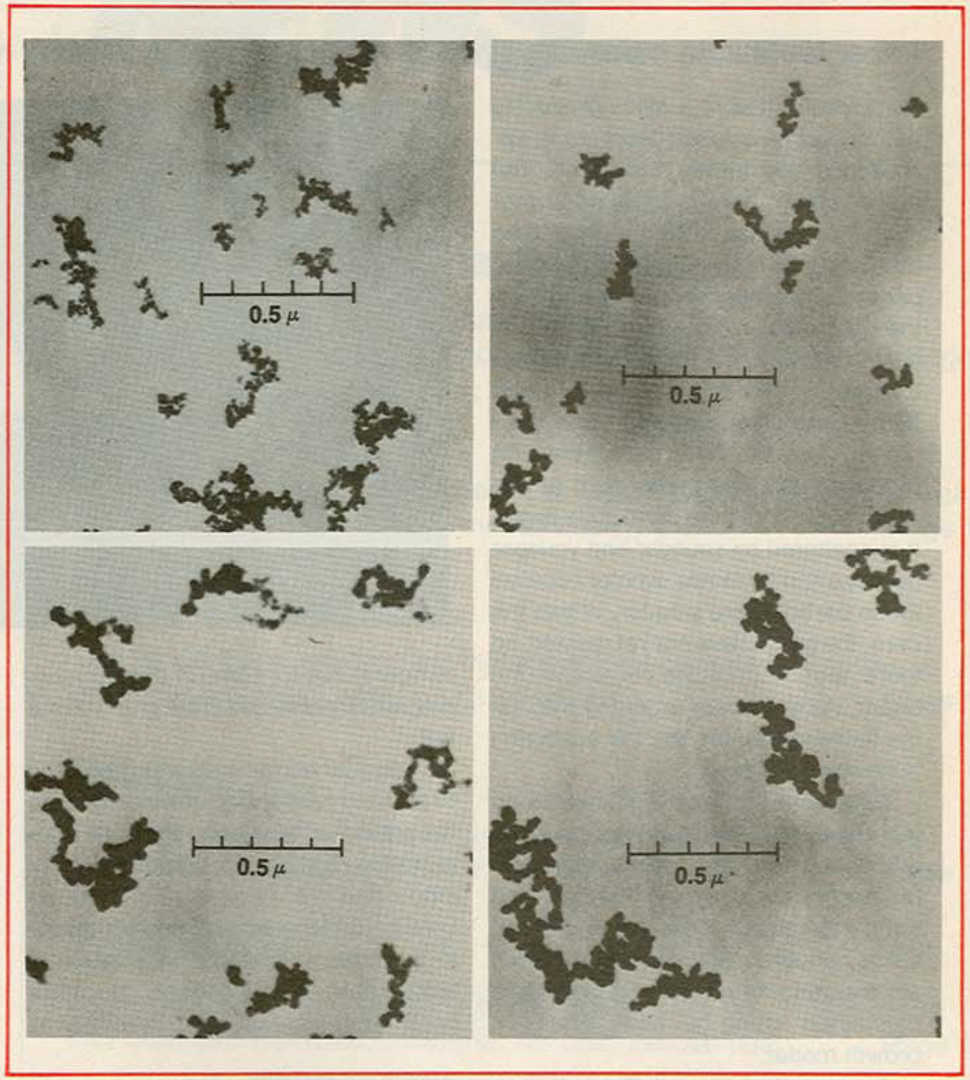
Page 22



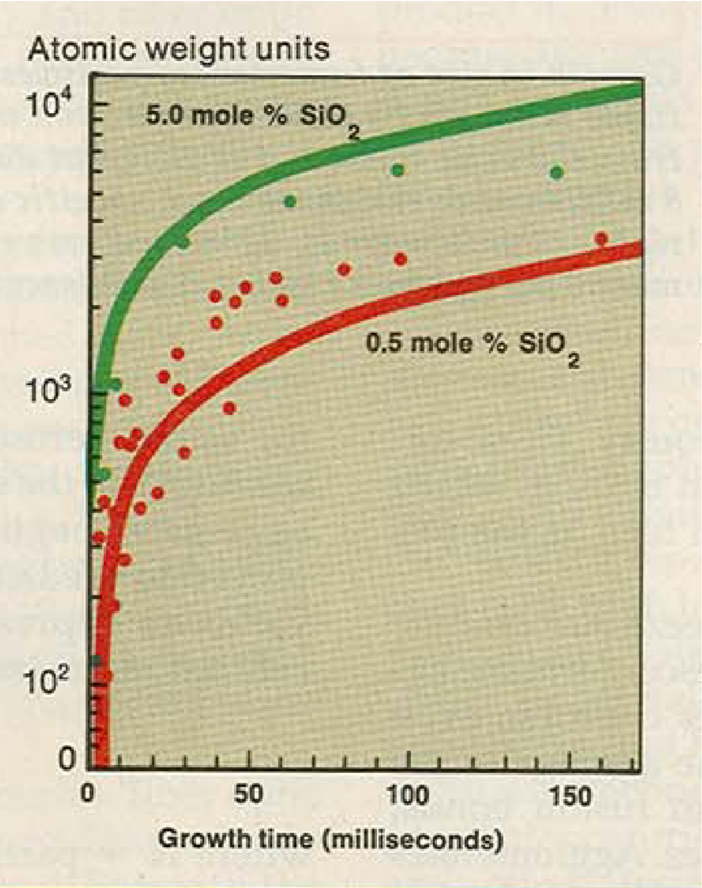
Collisions of flame-formed particles form larger aggregates and agglomerates



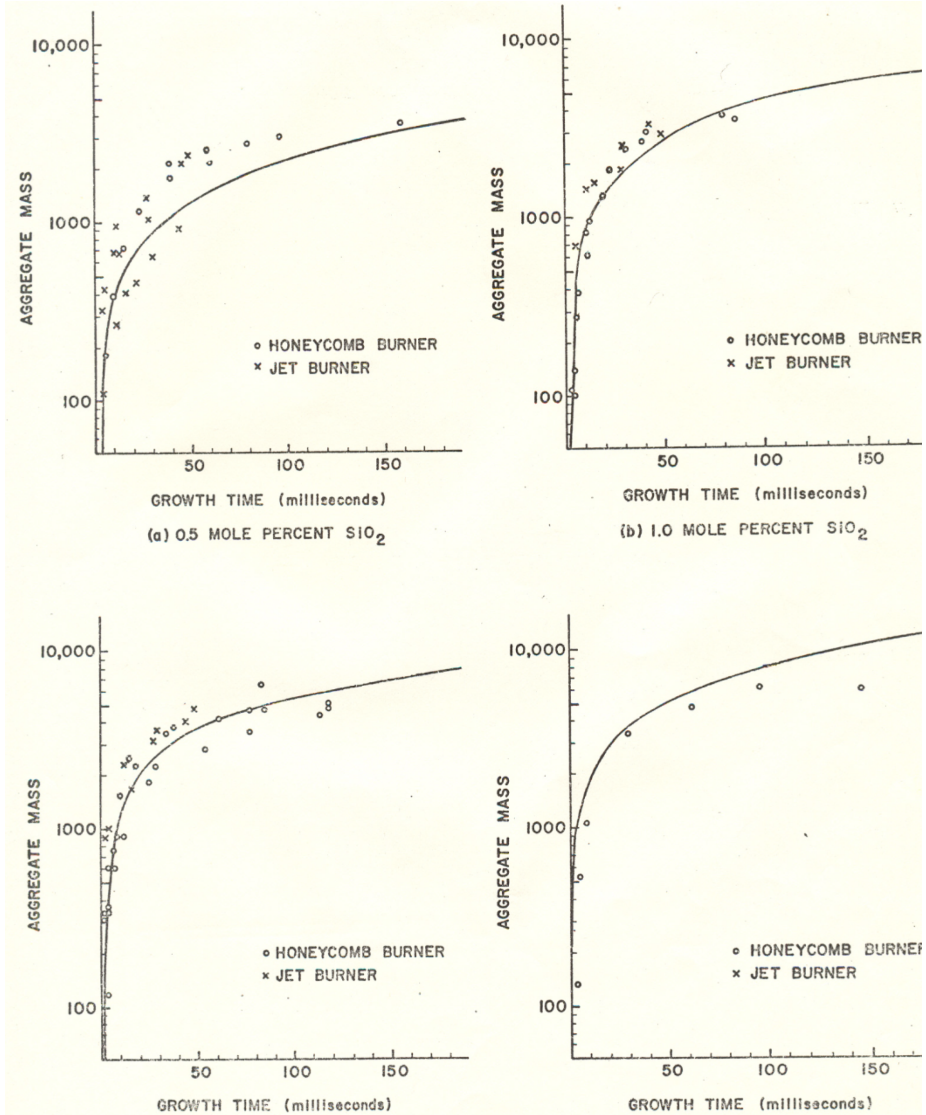
Fumed silica is formed when silicon tetrachloride reacts in a hydrogen flame to form single spherical droplets of silicon dioxide. These grow through collision and coalescence to form larger droplets. As the droplets cool and begin to freeze, but continue to collide, they stick but do not coalesce, forming solid aggregates, which in turn continue to collide to form clusters known as agglomerates



Growth in size of fumed silica particles as they are carried further from the flame is shown by these four electron micrographs. All samples were taken from the same flame but at different distances from the flame front: upper left, 8 milliseconds residence time, specific surface area 360 sq meters per g; upper right, 13 milliseconds, 350 sq meters per g; lower left, 86 milliseconds, 200 sq meters per g; lower right, 137 milliseconds, 150 sq meters per g



Atomic weight units
10^4
10^3
10^2
0
5.0 mole % SiO_2
0.5 mole % SiO_2
0
50
100
150
Growth time (milliseconds)

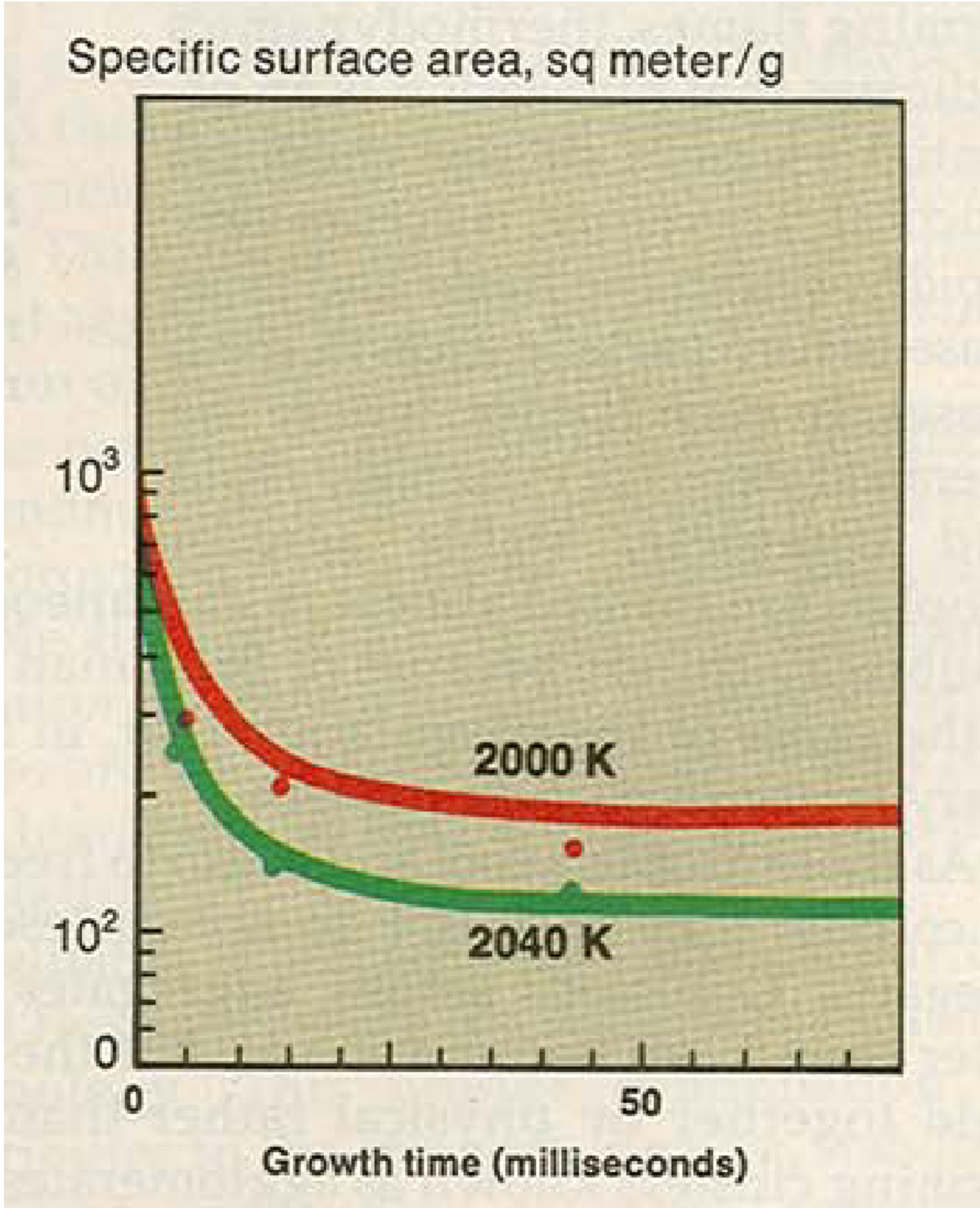


(a) 0.5 MOLE PERCENT SiO_2

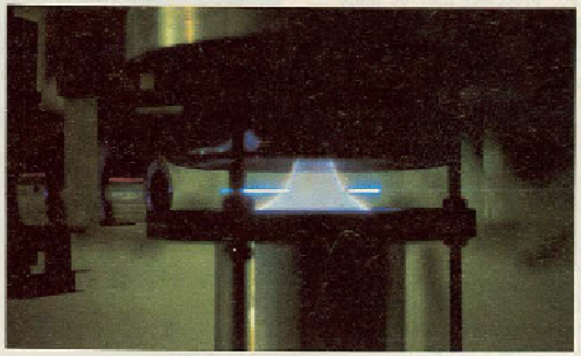
(b) 1.0 MOLE PERCENT SiO_2

(c) 2.0 MOLE PERCENT SiO_2

(d) 5.0 MOLE PERCENT SiO_2


Specific surface area, sq meter/g
10^3
10^2
0
2000 K
2040 K
0
50
Growth time (milliseconds)

Laser technique measures growth of silica particles as they move from flame



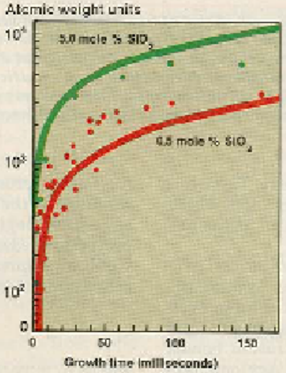
Particles formed in a silica-producing flame scatter a laser beam as it approaches and leaves the flame. The burner shown here is adjusted to produce a cone-shaped flame, rather than the flat flame shown in the diagram on page 26. The laser beam entering from the right initially is scattered slightly by dust in the room. It suddenly becomes brighter when it encounters larger flame-generated particles that have grown from the time they were first produced near the burner rim. As the beam approaches the core of the flame, it is scattered by younger and younger particles and becomes dimmer because these particles are smaller. Within the core, the gases have not yet reacted, so there are no particles to scatter the beam. As the beam emerges through the flame toward the left, this scattering behavior is reversed.

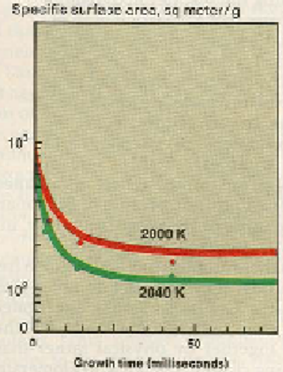
Data from this laser light-scattering technique are plotted as the points in the lefthand graph. The points represent measurements at varying flow rates and temperatures but at the same indicated silica concentration. The solid curves are theoretically predicted growth rates calculated using a comprehensive growth model.

As expected, coagulation rate is a strong function of concentration and aggregate population. It decreases dramatically as the population becomes smaller (or the aggregate mass becomes larger). The rather marked break in each curve coincides with a shift from free-molecule to continuum Brownian behavior [at aggregate masses of about 3000 × 10^6 atomic weight units (5 × 10^{-15} g) and aggregate diameters of about 400 nm in these flames].

Although aggregate mass is dependent on residence time and concentration, primary particle size is dictated by residence time and temperature. The lower right graph, for example, shows specific surface areas formed at two temperatures for some of the silica aggregates represented in the graph on the left.

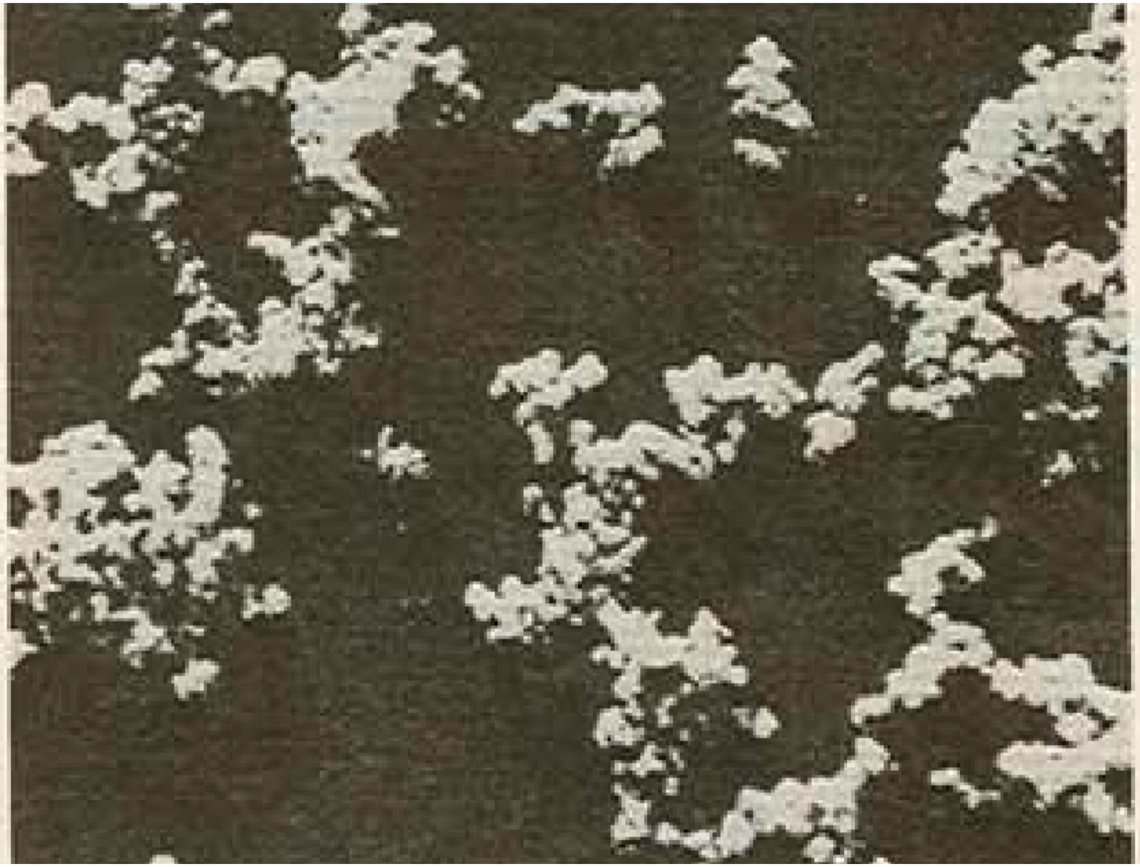
Classical fusion theory can be used to derive a relationship between particle diameter and residence time. To integrate the relationship, a boundary condition and the cooling rate must be known. (Surface tension, one parameter in the theory, is rather insensitive to temperature, but viscosity, the other parameter, increases exponentially as the particles cool, so that the cooling rate is vital.) This introduces some arbitrariness into the data fit. Nevertheless, using the same values for initial particle diameter and cooling rate, the two curves in the righthand graph were plotted using the theoretical fusion expression. The results, both theoretical and experimental, obviously are highly sensitive to temperature, as these curves are for flames that differ by only 40 K in temperature.





ticles are small and populous. Solids concentration and residence time are the most significant variables affecting particle population. Temperature is relatively unimportant until growing particles cool to the point where they no longer coalesce. Then, according to this idealized picture, growth ceases.

To test the model, one can study the growth of primary particles. Experiments involving titanium dioxide particles in a flame, lead aerosols in a shock tube, and carbon black particles under dilute conditions in a laboratory furnace all showed good agreement with the equation when a sticking coefficient of unity was used. Even though carbon black is not precipitated cleanly by the chemical reaction, the chemistry evidently occurs rapidly enough so that coagulation (of viscous tarry droplets or semisolid particles) controls growth in its



Fumed silica, more expensive than carbon black, has many specialty uses, including as a reinforcing agent or flow-control additive

Combustion Science and Technology Applied to the Design of a Particular Biomass Combustor

(Gael Ulrich 4 November 2014)

Three Ts of Combustion:

Time
Temperature
Turbulence

Four Cs of Consumerism:

Cost (has to be cheap)
Clean
Convenient
Compatible

Chemical/Combustion Engineering Approach—From Scratch:

US005678494A

United States Patent [19]

Ulrich

[11] **Patent Number:** **5,678,494**

[45] **Date of Patent:** **Oct. 21, 1997**

[54] **BIOMASS-FUELED FURNACE**

[76] Inventor: **Gael Ulrich**, 3 Ryan Way, Durham, N.H. 03824

[21] Appl. No.: **408,348**

[22] Filed: **Mar. 22, 1995**

[51] **Int. Cl.**[6] **F23G 5/04**

[52] **U.S. Cl.** **110/224**; 110/229; 110/251; 110/256; 110/257; 110/212; 110/302; 110/102

[58] **Field of Search** 110/102, 118, 110/224, 251, 254, 256, 257, 302, 304, 229, 210–212

[56] **References Cited**

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4,616,572	10/1986	Berthiller	110/254
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Primary Examiner—Henry A. Bennett
Assistant Examiner—Susanne C. Tinker
Attorney, Agent, or Firm—William B. Ritchie

[57] **ABSTRACT**

A biomass-fueled furnace for residential or institutional space and hot water heating. Wood chips, the preferred fuel, are purchased "green and/or wet" and are stored in a dryer/storage assembly which uses waste clean exhaust gases produced by the furnace to dry them. Wood chips are fed via gravity to the primary combustion chamber where, via pyrolysis, they are burned. A thimble combustor eliminates radiant heat loss from the primary pyrolysis zone, allowing stable pyrolysis at low burning rates. A second combustion chamber fed with pre-heated air completely oxidizes pyrolysis gases. This furnace is capable of operating continuously at extremely low fuel consumption rates so that heat release can be regulated by thermostat in the same manner as conventional gas and oil fired furnaces. A combination of fuel drying plus secondary air preheating by the secondary flame allows stable operation at extremely low or "idle" fuel rates. This eliminates the need for ignition except when a new furnace is placed in service or following a maintenance shut-down. The furnace shifts from idle to active mode through an increase in primary air rate when more heat is called for. Chips flow by gravity to the primary combustor with no need for mechanical feeders or conveyors. Combustion rates and chip feed rates are regulated simply by the primary air rate. Secondary air rates are adjusted accordingly to promote clean, efficient operation.

15 Claims, 3 Drawing Sheets

Design Principles (KISS test)

1. **Gravity feed of chips**

2. **Primary air rate controls chip feed rate.**

3. **Chips filter gas (minimize fly ash).**

4. **Primary gasification with secondary air to fine-tune combustion.**

5. **Preheat of secondary air ("temperature").**

6. **Primary air thimble promotes self-radiation.**

7. **"Moderate" combustion rather than stop and start.**

8. **Use waste heat to dry chips.**

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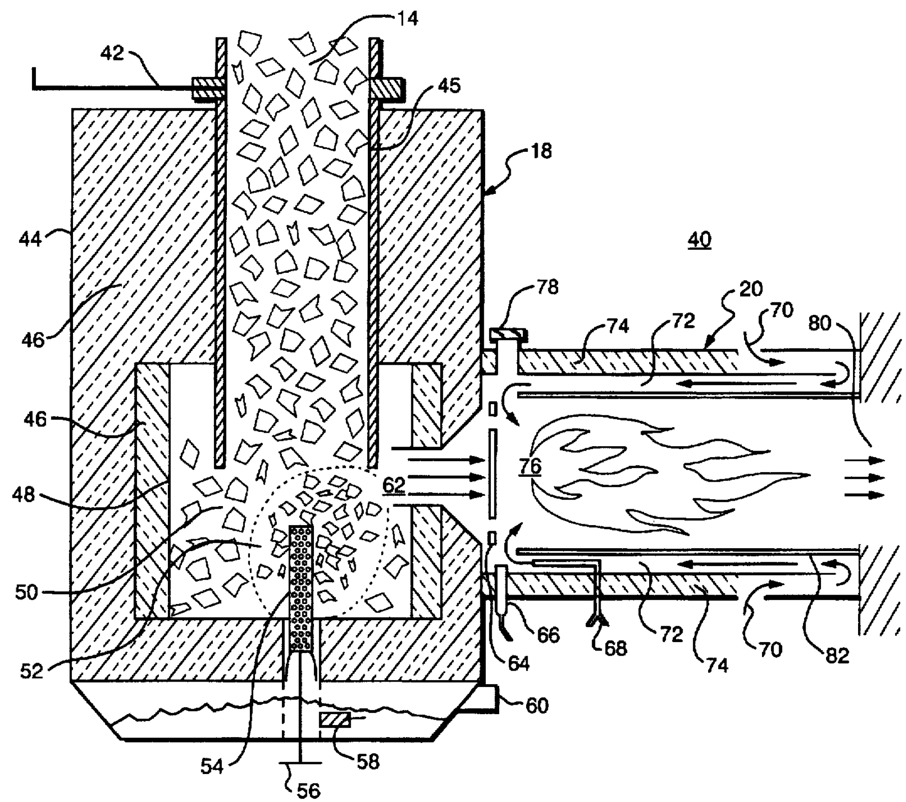
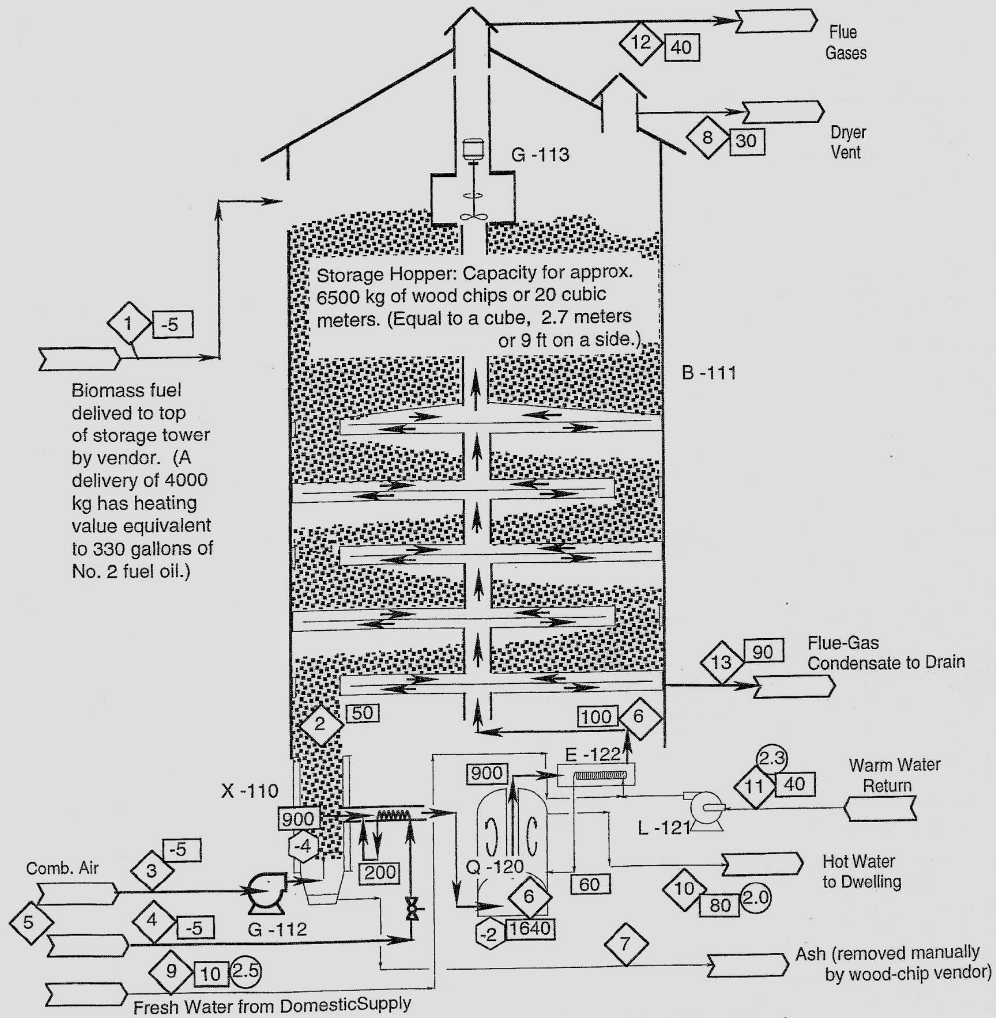
7. Moderate combustion rather than stop and start.

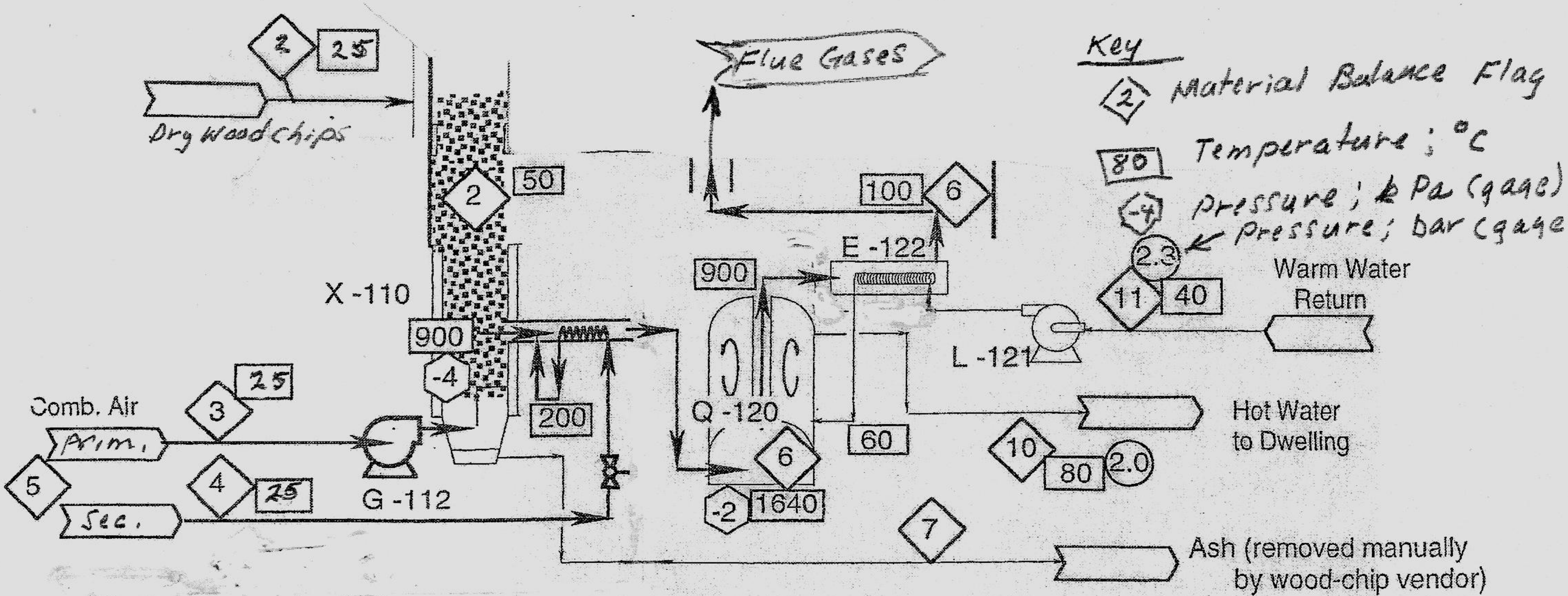
8. Use waste heat used to dry chips.





Mass Balance: grams per second (Basis: 8.0 g/s wood chips containing 50% moisture)

Component	m.w.	Raw Fuel ⟨1⟩	Dried Fuel ⟨2⟩	Primary Comb. Air ⟨3⟩	Secondary Comb. Air ⟨4⟩	Total Comb. Air ⟨5⟩	Combustion Products ⟨6⟩	Ash ⟨7⟩
C	12	1.76	1.76					
H	1	0.28	0.28					
O_2	32	1.90	1.90	3.05	3.05	6.1	1.0	
S	32	0.002	0.002					
Ash	--	0.06	0.06					0.06
H_2O	18	4.0	1.71	0.05	0.05	0.1	4.32	
N_2	28			10.0	10.0	20.0	20.0	
CO_2	44						6.5	
SO_2	64						0.004	
Total		8.0	5.7	13.1	13.1	26.2	31.8	0.06



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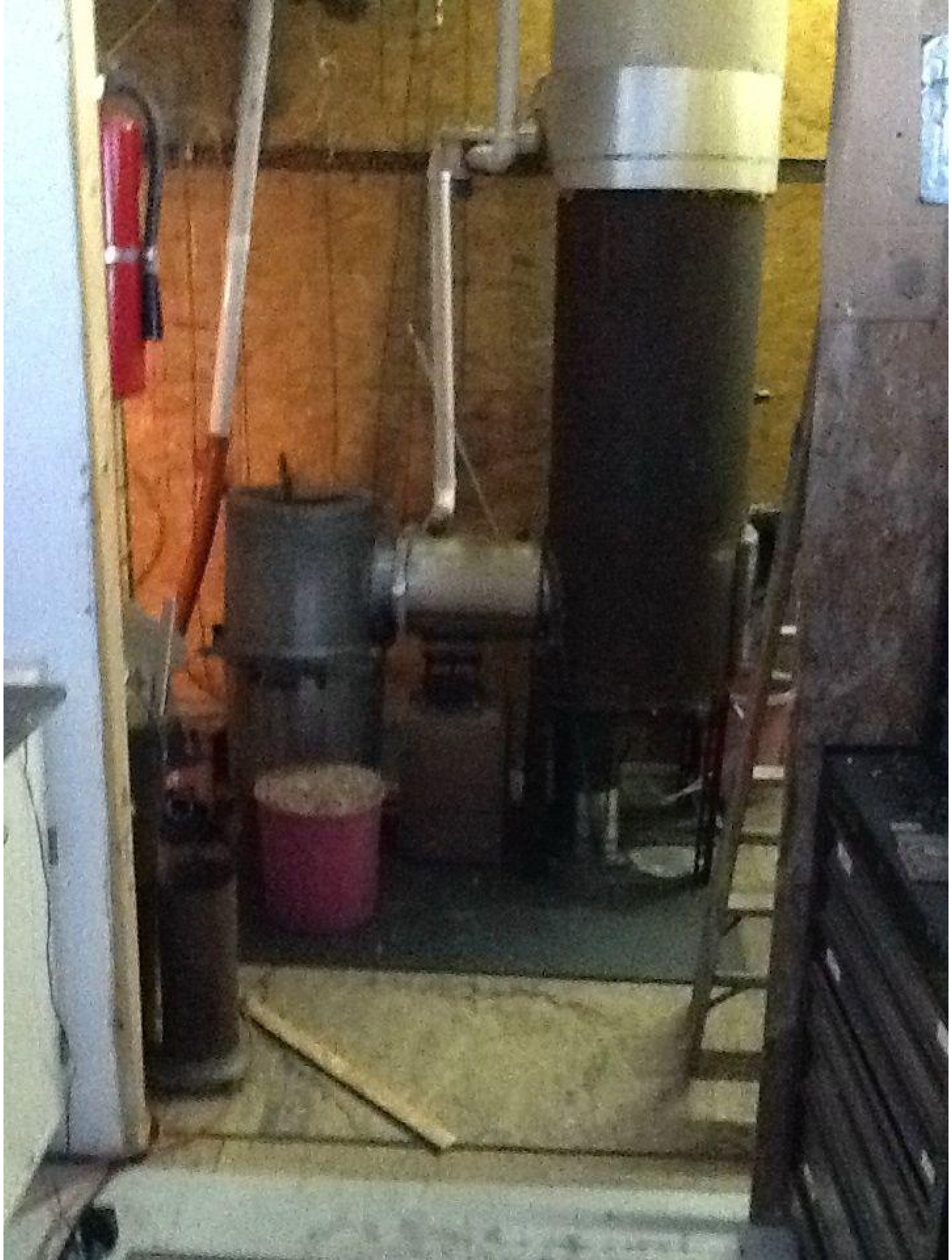
H	1	0.28	0.28					
O_2	32	1.90	1.90	3.05	3.05	6.1	1.0	
S	32	0.002	0.002					
Ash	--	0.06	0.06					0.06
H_2O	18	4.0	1.71	0.05	0.05	0.1	4.32	
N_2	28			10.0	10.0	20.0	20.0	
CO_2	44						6.5	
SO_2	64						0.004	
Total		8.0	5.7	13.1	13.1	26.2	31.8	0.06



“Good judgment comes from experience.

Experience comes from bad judgement.”

Designed using Theory. Practice revealed problem areas.

Chips are tough to feed.

- **Perfectly smooth tube**
- **Diverging angle**

Abandon use of waste heat to dry.

- **Too much extra trouble and cost.**

More sophistication needed with ash removal.

Efficiency challenge—getting high CO_2 with low "smoke."

(Temperature we have; getting time and turbulence is expensive [pressure drop and capital cost]. Decided to use another trick; subdivision.)

BERC Spreadsheet per Charles Niebling (January 2014 fuel prices)

Fuel Characterization Sheet

Fuel Type	Unit	Cost per Unit	BTU per Unit (dry)	Moisture Content	MMBtu per Unit	Cost per MMBtu Delivered	Average Seasonal Efficiency	Delivered MMBTU per Unit	Cost per MMBtu After Combustion
Natural Gas	therm	$1.30	100,000	0%	0.100	$13.00	85%	0.085	**$15.29**
Oil	gallon	$3.94	138,000	0%	0.138	$28.55	85%	0.117	**$33.59**
Propane	gallon	$3.67	92,000	0%	0.092	$39.89	85%	0.078	**$46.93**
Coal	ton	$266.00	25,000,000	0%	25.0	$10.64	75%	18.8	**$14.19**
Wood Pellets	ton (bulk delivered)	$243.00	16,800,000	4.5%	16.0	$15.15	85%	13.6	**$17.82**
Wood Pellets	ton (retail bagged)	$300.00	16,800,000	4.5%	16.0	$18.70	85%	13.6	**$22.00**
Cordwood	cord	$250.00		seasoned	22.0	$11.36	60%	13.2	**$18.94**
Wood Chips	ton	$55.00	16,800,000	45%	9.2	$5.95	65%	6.0	**$9.16**

NOTES

Wood:	Northeastern hardwoods (NRBP tests, early 1990s, 8 samples around the region)	8,200
	Standard assumption for wood	8,500
	Alternate assumption for wood	8,600
	Assumption used in this analysis	8,400
	Western softwoods (northern Rockies, developed for Darby)	9,000

Efficiency:
Gas - 60% for atmospheric burners
- 80% for modern, sealed combustion, well-maintained commercial boilers
- 85% for the best, professionally maintained industrial & large institutional boilers

Oil - 50-70% for old, poorly-maintained, oversized equipment
- 75% for modern, well-maintained commercial boilers
- 85% for the best, professionally maintained industrial & large institutional boilers

Wood - 65% for modern chip boilers
- 50-60% for big old industrial wood boilers
- 50% for old wood stoves
- 60% for EPA certified wood stoves
- 75% for water storage boilers (GARN, Tarm)
- 85% for sealed combustion pellet burners

Fuel Type	Unit	Cost per Unit	BTU per Unit (dry)	Moisture Content	MMBtu per Unit	Cost per MMBtu Delivered	Average Seasonal Efficiency	Delivered MMBTU per Unit	Cost per MMBtu After Combustion
Natural Gas	therm	$1.30	100,000	0%	0.100	$13.00	85%	0.085	$15.29
Oil	gallon	$3.94	138,000	0%	0.138	$28.55	85%	0.117	$33.59
Propane	gallon	$3.67	92,000	0%	0.092	$39.89	85%	0.078	$46.93
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Wood Pellets	ton (bulk delivered)	$243.00	16,800,000	4.5%	16.0	$15.15	85%	13.6	$17.82
Wood Pellets	ton (retail bagged)	$265.00	16,800,000	4.5%	16.0	$16.52	85%	13.6	$19.43
Cordwood	cord	$250.00		seasoned	22.0	$11.36	60%	13.2	$18.94
Wood Chips	ton	$55.00	16,800,000	45%	9.2	$5.95	65%	6.0	$9.16

Spreadsheet modified by Ulrich (January 2014 fuel prices)

Fuel Characterization Sheet

Fuel Type	**Unit**	**Cost per Unit**	**BTU per Unit (dry)**	**Moisture Content**	**MMBtu per Unit**	**Cost per MMBtu Delivered**	**Average Seasonal Efficiency**	**Delivered MMBTU per Unit**	**Cost per MMBtu After Combustion**
Natural Gas	therm	$1.30	100,000	0%	0.100	$13.00	90%	0.090	$14.44
Oil	gallon	$3.94	138,000	0%	0.138	$28.55	80%	0.110	$35.69
Propane	gallon	$3.67	92,000	0%	0.092	$39.89	85%	0.078	$46.93
Coal	ton	$266.00	25,000,000	0%	25.0	$10.64	75%	18.8	$14.19
Wood Pellets	ton (bulk delivered)	$243.00	15,500,000	4.5%	14.8	$16.42	80%	11.8	$20.52
Wood Pellets	ton (retail bagged)	$265.00	16,400,000	4.5%	15.7	$16.92	75%	11.7	$22.56
Pallet Shards	ton	$80.00	16,400,000	20.0%	13.1	$6.10	65%	8.5	$9.38
Cordwood	cord	$250.00		seasoned	22.0	$11.36	60%	13.2	$18.94
Sorted Trash	ton	($100.00)	18,000,000	10%	16.2	($6.17)	65%	10.5	($9.50)
Wood Chips	ton	$55.00	16,800,000	45%	9.2	$5.95	65%	6.0	$9.16

Ulrich Spreadsheet (November 2014 fuel prices)

Fuel Characterization Sheet

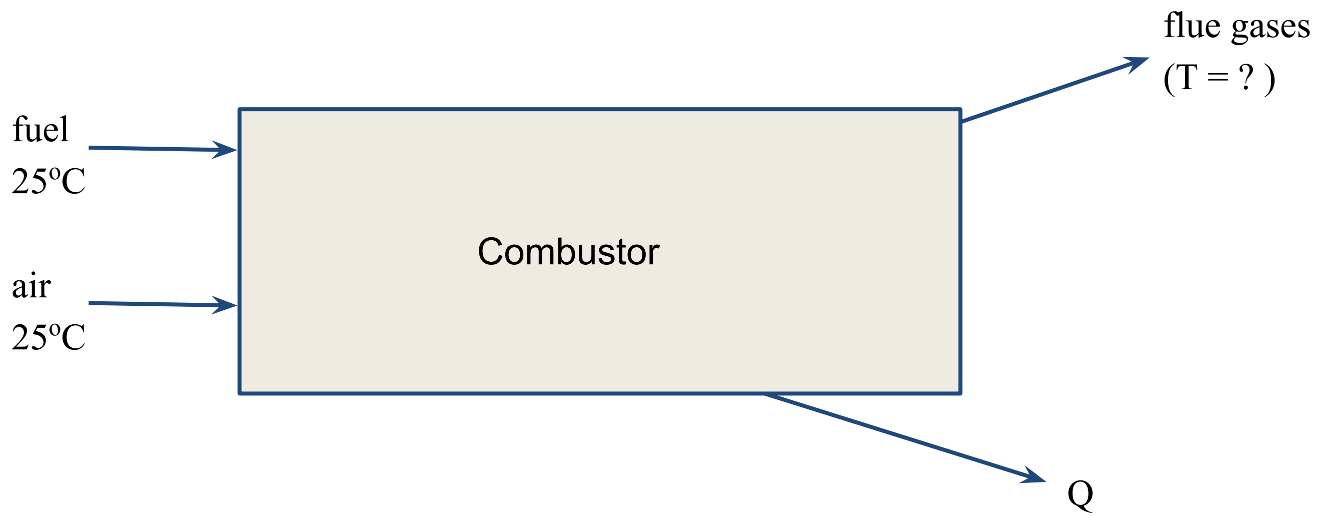
Fuel Type	Unit	Cost per Unit	BTU per Unit (dry basis [maf])	Moisture & Ash Content	MMBtu per Unit (maf)	Cost per MMBtu (maf)	Average Seasonal Efficiency	Delivered MMBTU per Unit	Cost per MMBtu After Combustion
Natural Gas	therm	$1.50	100,000	0%	0.100	$15.00	90%	0.090	$16.67
Oil	gallon	$3.30	138,000	0%	0.138	$23.91	80%	0.110	$29.89
Propane	gallon	$3.20	92,000	0%	0.092	$34.78	85%	0.078	$40.92
Coal	ton	$266.00	25,000,000	0%	25.0	$10.64	75%	18.8	$14.19
Wood Pellets	ton (bulk delivered)	$250.00	16,800,000	4.5%	16.0	$15.58	78%	12.5	$19.98
Wood Pellets	ton (retail bagged)	$300.00	16,800,000	4.5%	16.0	$18.70	75%	12.0	$24.93
Pallet Shards	ton	$100.00	16,800,000	20.0%	13.4	$7.44	65%	8.7	$11.45
Cordwood	cord	$325.00		seasoned	22.0	$14.77	70%	15.4	$21.10
Sorted Trash	ton	($100.00)	18,000,000	10%	16.2	($6.17)	65%	10.5	($9.50)
Wood Chips	ton	$65.00	16,800,000	45%	9.2	$7.03	65%	6.0	$10.82

Efficiency Analysis and Measurement in Biocombustors

Tools:
Thermodynamics 101: Enthalpy

1. **Energy content of matter**
   (Btu/lb in old days; J/g or kJ/kg, or kJ/g now)
2. **Point function**
3. **A Property of matter**
   (Tell me the chemical composition, temperature and pressure, and I can give you a number.)

Chemical Engineering Approach ("Black Box")



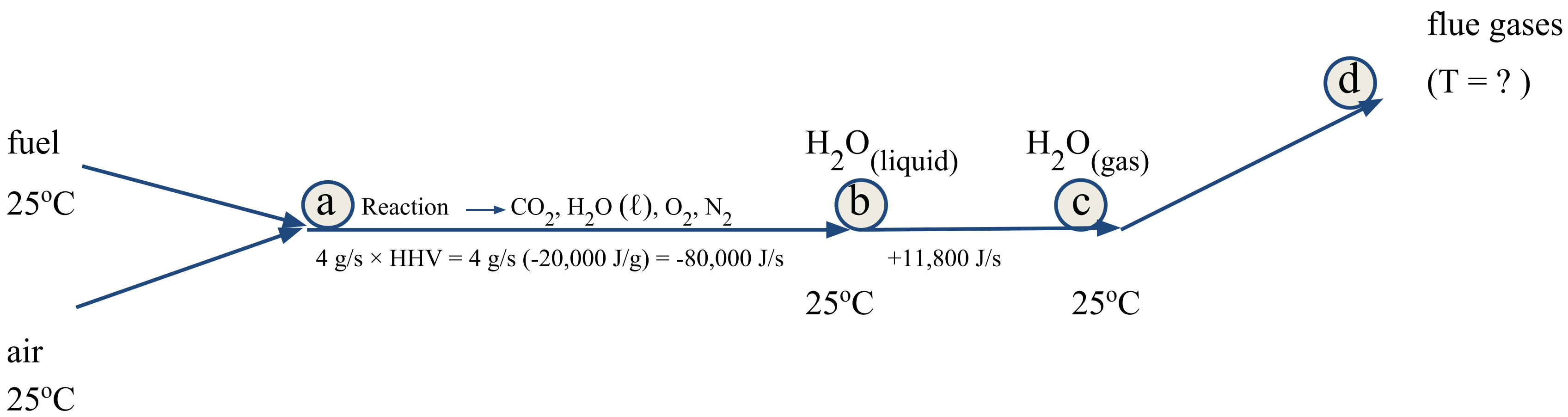
$$\text{Efficiency } \mathcal{E} = \frac{Q}{\text{Fuel Energy}}$$

What are **Q** and **Fuel Energy**? (To answer, consider first what the temperature would be with no heat removed.)

Adiabatic Flame Temperature:

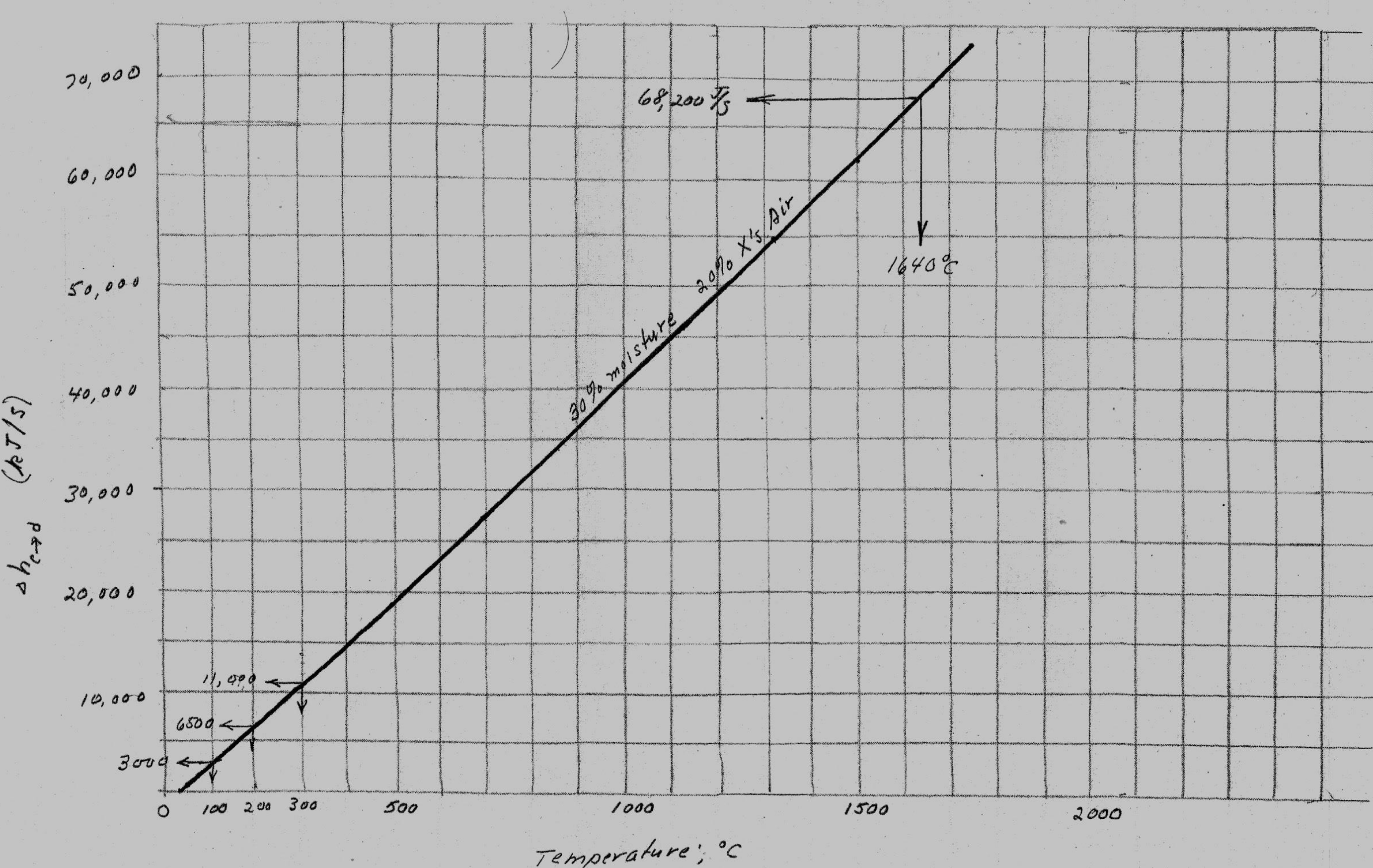
(Black box above with Q = O; $\nabla h = Q = 0$)

Enthalpy Path (I can choose any path I want [convenience, not nature])



$$\Delta h_{a \rightarrow b} + \Delta h_{b \rightarrow c} + \Delta h_{c \rightarrow d} = 0$$

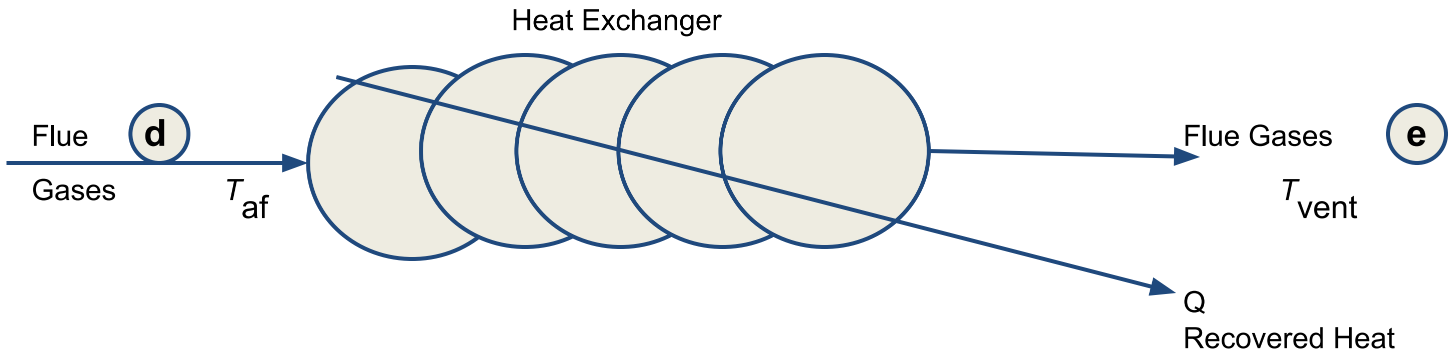
$$\Delta h_{c \rightarrow d} = - \Delta h_{b \rightarrow c} - \Delta h_{c \rightarrow d} = 80{,}000 \text{ J/s} - 11{,}800 \text{ J/s} = 68{,}200 \text{ J/s}$$


70,000
60,000
50,000
40,000
30,000
20,000
10,000
11,000
6500
3000
68,200 J/S
1640°C
30% moisture
20% X's Air
$\Delta h_{c\to d}$ (kJ/s)
0
100
200
300
500
1000
1500
2000
Temperature; °C

(Adiabatic flame temperature is that corresponding to $\Delta h_{c\text{-}d}$ = **68,200 J/s** or **1640°C**)

Back to the question: what are **Q** and **Fuel Energy**?

Q is equal to $\Delta h_{d\text{-}e}$ (where h_e is defined by the exit temperature)



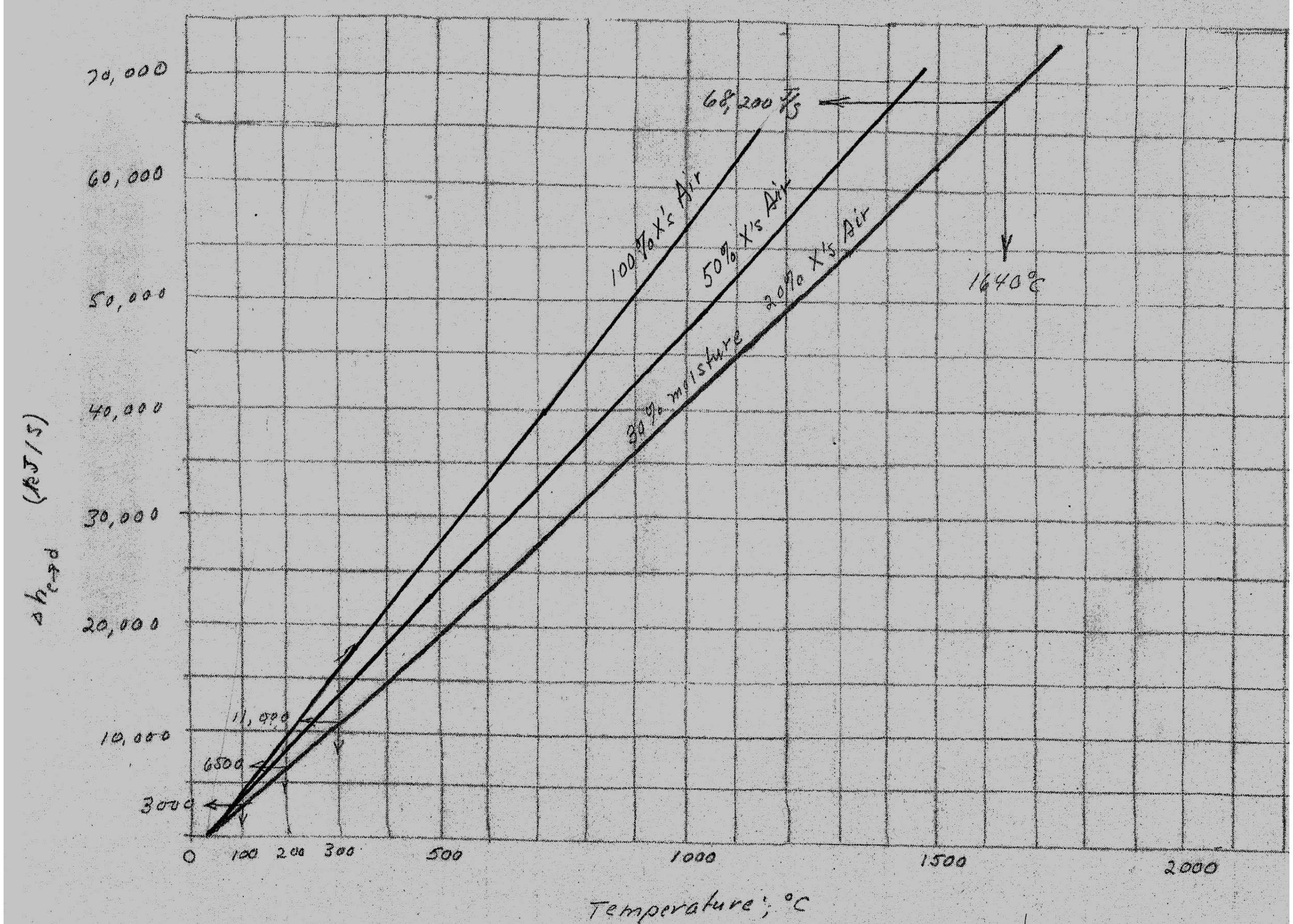
For t_e at 100°C, $\Delta h_{d\text{-}e}$ = Q = 68,200 J/s – 3000J/s = 65,200 j/s

Fuel Energy is equal to $\Delta h_{a\text{-}b}$ (the higher heating value or heat of combustion)

For this case; 4 g/s bone dry wood, $\Delta h_{a\text{-}b}$ = (4 g/s) (20 kJ/g)= 80,000 J/s

Efficiency:

$$\text{Efficiency } \mathcal{E} = \frac{65{,}200 \text{ J/s}}{80{,}000 \text{ J/s}} \times 100 = 81.5\%$$


70,000
60,000
50,000
40,000
30,000
20,000
10,000
68,200 #/S
1640°C
100% X's Air
50% X's Air
20% X's Air
30% moisture
11,000
6500
3000
0
100
200
300
500
1000
1500
2000
Temperature; °C

(Adiabatic flame temperature is that corresponding to $\Delta h_{c\text{-}d}$ = **68,200 J/s** or **1640°C**)

Back to the question: what are **Q** and **Fuel Energy**?

Q is equal to $\Delta h_{d\text{-}e}$ (where h_e is defined by the exit temperature)
For t_e at 100°C, $\Delta h_{d\text{-}e}$ = Q = 68,200 J/s – 3000J/s = 65,200 j/s

Fuel Energy is equal to $\Delta h_{a\text{-}b}$ (the higher heating value or heat of combustion)
For this case; 4 g/s bone dry wood, $\Delta h_{a\text{-}b}$ = (4 g/s) (20 kJ/g)= 80,000 J/s

Efficiency:

$$\text{Efficiency } \mathcal{E} = \frac{65{,}200 \text{ J/s}}{80{,}000 \text{ J/s}} \times 100 = 81.5\%$$

Where do we loose efficiency?

1. **Flue Gas Temperature**

At t_e = 200°C, $\Delta h_{d\text{-}e}$ = Q = 68,200-6500 = 61,700 J/s; $\mathcal{E}$ = 77%

At t_6 = 300°C, $\Delta h_{d\text{-}e}$ = Q = 68,200-11,000 =57,200 J/s; $\mathcal{E}$ = 71.5%

2. **Incomplete Combustion**

At 10% of fuel unburned, t_{fg} = 100°C; $\Delta h_{d\text{-}e}$ = 60,000 J/s; t_{af}= 1450°C;

$\mathcal{E}$ = (60,000 /80,000) x 100 = 75%

3. **Excessive Combustion Air**

(Exhibit E-6)

At 50% excess air (150% of stoichiometric or theoretical air), t_{fg} = 200°C; $\Delta h_{c\text{-}d}$ = 68,200; t_{af}= 1425°C; $\Delta h_{d\text{-}e}$ =68,200– 8000 = 60,200 J/s

$\mathcal{E}$ = 60,200 /80,000 x 100 = 75%

At 100% excess air (200% of stoichiometric or theoretical air), t_{fg} = 200°C; $\Delta h_{c\text{-}d}$ = 68,200; t_{af}= 1200°C; $\Delta h_{d\text{-}e}$ =68,200– 10,000 = 58,200 J/s;

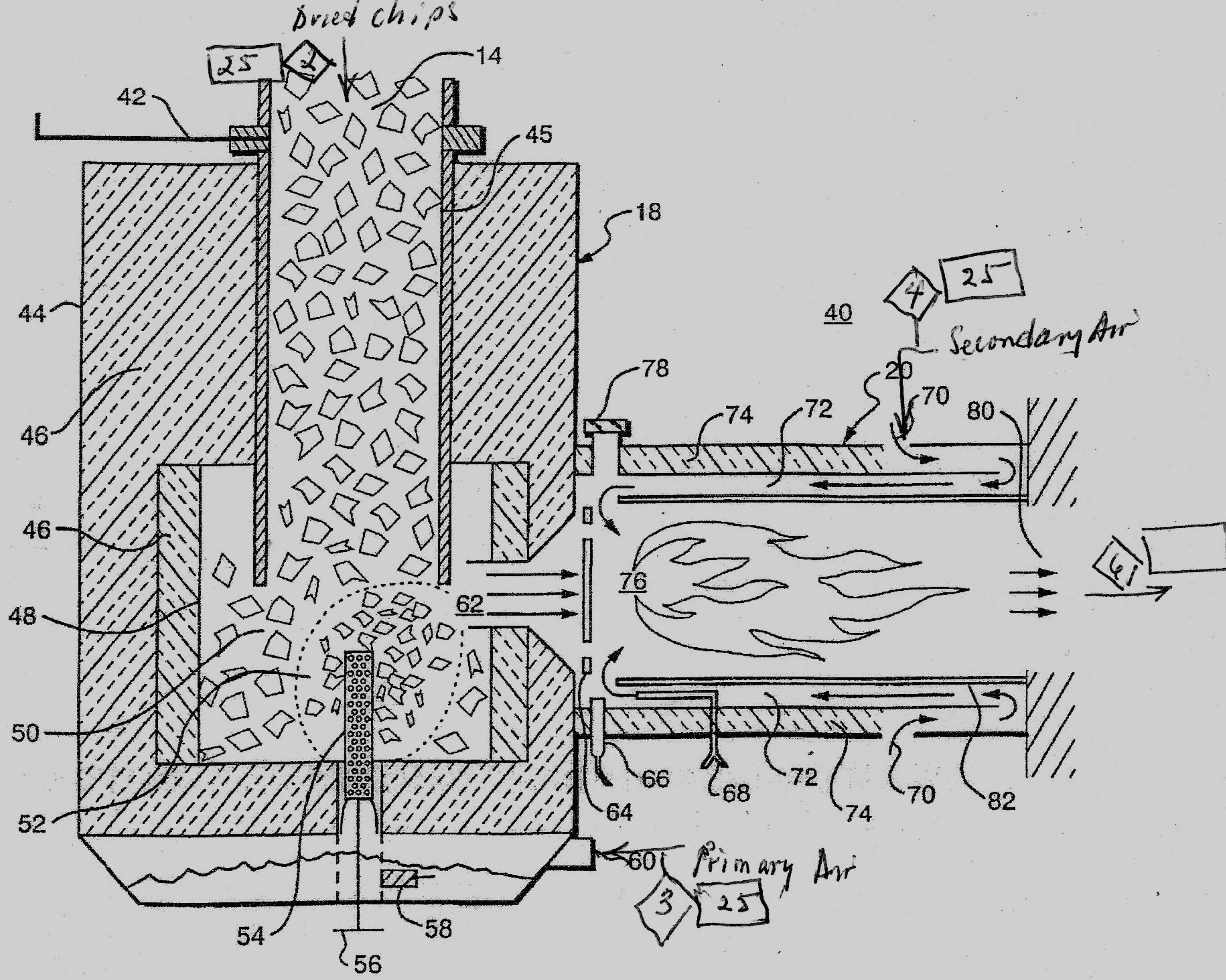
$\mathcal{E}$ = 58,200 /80,000 x 100 = 73%

4. **Excessive Moisture**

Requires heat to drive off and carries with flue gases out the chimney. Also retards reaction rates/dampens combustion intensity.

What does one need to determine efficiency?

Flue gas temperature and composition (plus assurance that there is no CO or unreacted fuel or know their quantities)



Dried chips
25
2
14
42
45
18
44
46
46
48
50
52
54
56
58
60
Primary Air
3
25
62
64
66
68
72
74
70
82
76
78
74
72
20
70
80
40
4
25
Secondary Air
6

Flame-Generated Fine Oxide Particles

Gael Ulrich
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SURFACE AREA = 358 M^2/G

(a)

SURFACE AREA = 349 M^2/G

(b)

SURFACE AREA = 203 M^2/G

(c)

SURFACE AREA = 151 M^2/G

(d)