BBE 4414/5414: Advanced Building Science

- General Mechanical & Heating Systems
  - General mechanical considerations
  - Combustion
  - Residential heating equipment
- Readings
  - HF Chapter 28
  - Heating Handout

All-Air HVAC Schematic

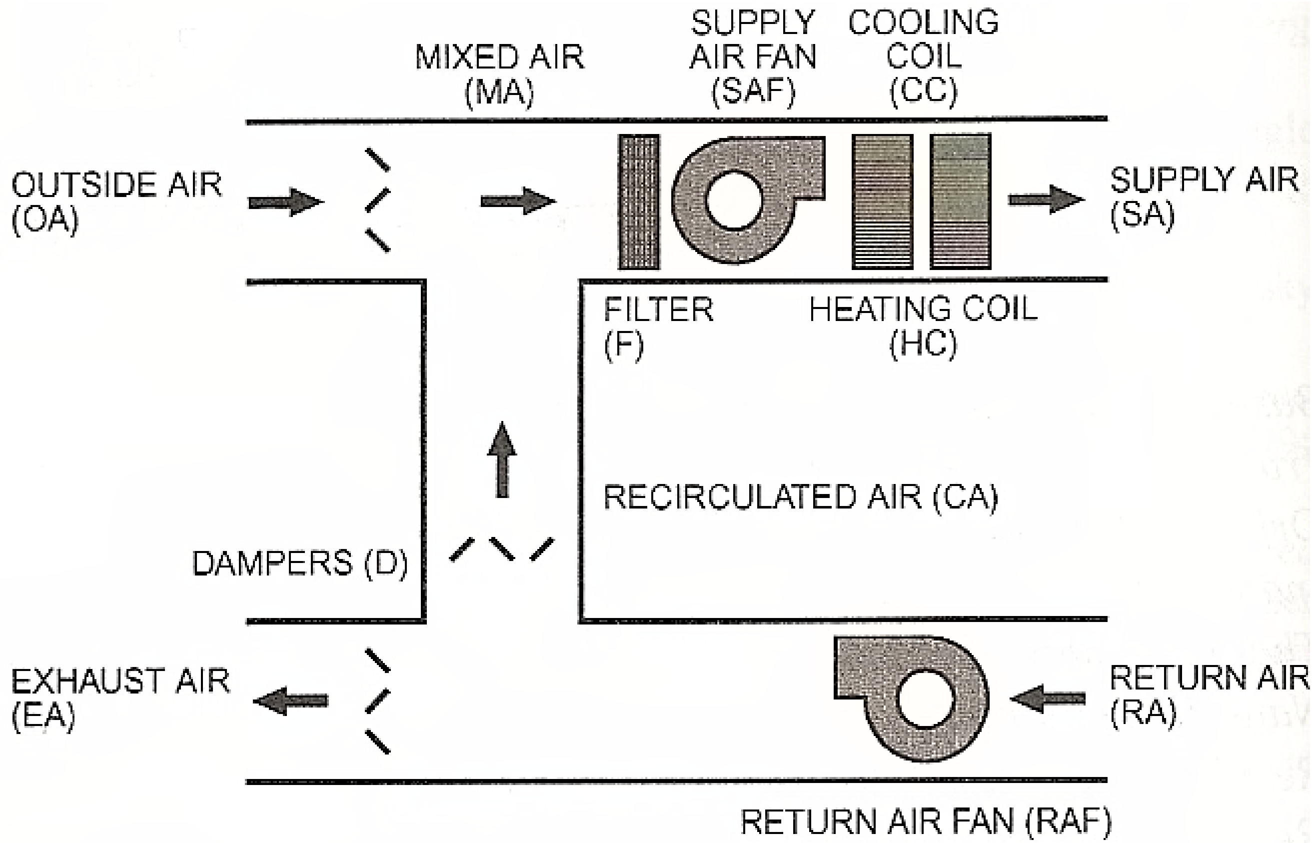

Fig. 2 Simple All-Air Air-Handling Unit with Associated Airflows

Source: ASHRAE Handbook Fundamentals 2013, Chapter 16.2

Residential Systems – HVAC

- Heating
  - Hydronic radiator used to be very common
  - Forced air is big today, especially in the Midwest
  - Hydronic (primarily in-floor) is growing
- Ventilation
  - Relatively new
  - Started out as bath and kitchen fans
  - Now whole house approaches/equipment
- Air-Conditioning (Cooling?)
  - Has gone from none to room to central air

Residential Systems – Other

- Circulation & Distribution
  - Internal circulation/distribution is important for comfort
  - It is useful for moisture averaging
  - Can be critical for good air quality
- Filtration
  - Forced-air filtration is pretty common, but generally poor
  - Stand-alone room and whole house filtration are growing
- Humidification / Dehumidification
  - Humidification went from none to almost all to some in heating climates
  - Dehumidification is moving from basement floor models to whole house approaches/equipment

Mechanical Systems

Life Cycle Energy Costs

- Initial costs
  - equipment of material costs
  - installation costs

- Operating costs
  - energy expenditures
  - maintenance costs

Fuel Cost Comparison – $ per MBtu

Table 4-1: Heating fuel cost comparison.

Fuel	Quantity for one million Btu's		Fuel price		Annual efficiency		Fuel Cost per million Btu's
Natural gas	10.0 Ccf	x	$______ per Ccf	/	(0.80 or ______)	=	______
LP gas.	11.11 gal.	x	$______ per gal.	/	(0.80 or ______)	=	______
Fuel oil	7.14 gal.	x	$______ per gal.	/	(0.75 or ______)	=	______
Electricity (resistance)	293 kWh	x	$______ per kWh	/	(1.00 or ______)	=	______
Electricity (air heat pump)	293 kWh	x	$______ per kWh	/	(1.50* or ______)	=	______
Electricity (water heat pump)	293 kWh	x	$______ per kWh	/	(3.00* or ______)	=	______
Mixed woods	0.0476.	x	$______ per cord	/	(0.50 or ______)	=	______
Kerosene	7.41 gal.	x	$______ per gal.	/	(0.85 or ______)	=	______

* This figure represents the efficiency of the heat pump. Usually called the coefficient of performance (COP) the heat output of the unit is divided by the electricity used.

Units:

Ccf	=	100 cubic feet of gas
therm	=	about 1 Ccf
kWh	=	1 kilowatt hour
cord	=	4 x 4 x 8 foot stack of wood

Mechanical Systems

True Cost of Energy

- Direct cost of fuel/electricity
  - customer fee
  - distribution fee
  - consumption fee
- Indirect costs of energy
  - subsidies, tax incentives, etc.
- Externalities
  - environmental impacts
  - health risks

Heating Equipment

Heating Equipment

- Principles of combustion
  - fuels
  - combustion calculations
- Burners
- Residential furnaces
- Commercial furnaces
- Boilers
- Terminal units
- Electric heating

Heating Equipment

Principles of Combustion

- Hydrocarbons + oxygen => heat + carbon dioxide + water
  - also nitrogen oxides, aldehydes
  - may be sulfur oxides, carbon monoxide
- Conditions that promote incomplete combustion
  - insufficient air and fuel mixing
  - insufficient air supply
  - insufficient residence time
  - flame impingement
  - too low flame temperature
- Heating value
  - high heating value includes condensed water vapor

Heating Equipment

- Fuels
  - Gases: Btu/ft.^{3}
  - Liquids: Btu/gal.
  - Solids: Btu/lb.

- Combustion Calculations
  - important, but beyond the scope of this class
  - if interested, see ASHRAE Handbook

Heating Values

Table 3 Heating Values of Substances Occurring in Common Fuels

Substance	Molecular Formula	Higher Heating Values,[a] Btu/ft^3	Higher Heating Values,[a] Btu/lb	Lower Heating Values,[a] Btu/lb	Specific Volume,[b] ft^3/lb
Carbon (to CO)	C	—	3,950	3,950	—
Carbon (to CO_2)	C	—	14,093	14,093	—
Carbon monoxide	CO	321	4,347	4,347	13.5
Hydrogen	H_2	325	61,095	51,623	188.0
Methane	CH_4	1012	23,875	21,495	23.6
Ethane	C_2H_6	1773	22,323	20,418	12.5
Propane	C_3H_8	2524	21,669	19,937	8.36
Butane	C_4H_{10}	3271	21,321	19,678	6.32
Ethylene	C_2H_4	1604[c]	21,636	20,275	—
Propylene	C_3H_6	2340[c]	21,048	19,687	9.01
Acetylene	C_2H_2	1477	21,502	20,769	14.3
Sulfur (to SO_2)	S	—	3,980	3,980	—
Sulfur (to SO_3)	S	—	5,940	5,940	—
Hydrogen sulfide	H_2S	646	7,097	6,537	11.0

Adapted from *Gas Engineers Handbook* (1965).

[a]All values corrected to 60°F, 30 in. Hg, dry. For gases saturated with water vapor at 60°F, deduct 1.74% of value to adjust for gas volume displaced by water vapor.

[b]At 32°F and 29.92 in. Hg.

[c]*North American Combustion Handbook* (1986).

Source: ASHRAE Handbook Fundamentals 2013 Chapter 28.2

Heating Values for Gas

Table 19-2 Heating Values of Gaseous Fuels

Gas	Btu/ft^3	MJ/m^3	Specific Gravity Air = 1.0
Natural	1030	38.4	0.60
Propane	2500	93.1	1.53
Butane	3175	118.3	2.00

Source: Howell, Sauer, & Coad, Principles of Heating, Ventilating, & Air Conditioning, 1997, Chapter 19.3

Heating Values for Liquids

Table 6 Typical API Gravity, Density, and Higher Heating Value of Standard Grades of Fuel Oil

Grade No.	API Gravity	Density, lb/gal	Higher Heating Value, Btu/gal
1	38 to 45	6.950 to 6.675	137,000 to 132,900
2	30 to 38	7.296 to 6.960	141,800 to 137,000
4	20 to 28	7.787 to 7.396	148,100 to 143,100
5L	17 to 22	7.940 to 7.686	150,000 to 146,800
5H	14 to 18	8.080 to 7.890	152,000 to 149,400
6	8 to 15	8.448 to 8.053	155,900 to 151,300

Source: ASHRAE Handbook Fundamentals 2013, 28.7

Heating Values for Solids

Table 19-4 Heating Value of Coal

Rank	Heating Value As Received Btu/lb	Heating Value As Received MJ/kg
Anthracite	12,700	29.5
Semianthracite	13,600	31.6
Low-volatile bituminous	14,350	33.4
Medium-volatile bituminous	14,000	32.6
High-volatile bituminous A	13,800	32.1
High-volatile bituminous B	12,500	29.1
High-volatile bituminous C	11,000	25.6
Subbituminous B	9000	20.9
Subbituminous C	8500	19.8
Lignite	6900	16.0

Source: Howell, Sauer, & Coad, Principles of Heating, Ventilating, & Air Conditioning, 1997, Chapter 19.3

Heating Values for Solids

Table 8 Typical Ultimate Analyses for Coals

Rank	As Received, Btu/lb	Constituents, Percent by Mass					
		O	H	C	N	S	Ash
Anthracite	12,700	5.0	2.9	80.0	0.9	0.7	10.5
Semianthracite	13,600	5.0	3.9	80.4	1.1	1.1	8.5
Low-volatile bituminous	14,350	5.0	4.7	81.7	1.4	1.2	6.0
Medium-volatile bituminous	14,000	5.0	5.0	81.4	1.4	1.5	6.0
High-volatile bituminous							
Type A	13,800	9.3	5.3	75.9	1.5	1.5	6.5
B	12,500	13.8	5.5	67.8	1.4	3.0	8.5
C	11,000	20.6	5.8	59.6	1.1	3.5	9.4
Subbituminous							
Type B	9,000	29.5	6.2	52.5	1.0	1.0	9.8
C	8,500	35.7	6.5	46.4	0.8	1.0	9.6
Lignite	6,900	44.0	6.9	40.1	0.7	1.0	7.3

Source: ASHRAE Handbook Fundamentals 2013, 28.9

Stoichiometric Reactions

Table 1 Combustion Reactions of Common Fuel Constituents

Constituent	Molecular Formula	Combustion Reactions	Stoichiometric Oxygen and Air Requirements: lb/lb Fuel[a] O_2	lb/lb Fuel[a] Air	ft³/ft³ Fuel O_2	ft³/ft³ Fuel Air	Flue Gas from Stoichiometric Combustion with Air: Ultimate CO_2, %	Dew Point,[c] °F	ft³/ft³ Fuel CO_2	ft³/ft³ Fuel H_2O	lb/lb Fuel CO_2	lb/lb Fuel H_2O
Carbon (to CO)	C	$C + 0.5O_2 \rightarrow CO$	1.33	5.75	b	b	—	—	—	—	—	—
Carbon (to CO_2)	C	$C + O_2 \rightarrow CO_2$	2.66	11.51	b	b	29.30	—	—	—	3.664	—
Carbon monoxide	CO	$CO + 0.5O_2 \rightarrow CO_2$	0.57	2.47	0.50	2.39	34.70	—	1.0	—	1.571	—
Hydrogen	H_2	$H_2 + 0.5O_2 \rightarrow H_2O$	7.94	34.28	0.50	2.39	—	162	—	1.0	—	8.937
Methane	CH_4	$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$	3.99	17.24	2.00	9.57	11.73	139	1.0	2.0	2.744	2.246
Ethane	C_2H_6	$C_2H_6 + 3.5O_2 \rightarrow 2CO_2 + 3H_2O$	3.72	16.09	3.50	16.75	13.18	134	2.0	3.0	2.927	1.798
Propane	C_3H_8	$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$	3.63	15.68	5.00	23.95	13.75	131	3.0	4.0	2.994	1.634
Butane	C_4H_{10}	$C_4H_{10} + 6.5O_2 \rightarrow 4CO_2 + 5H_2O$	3.58	15.47	6.50	31.14	14.05	129	4.0	5.0	3.029	1.550
Alkanes	C_nH_{2n+2}	$C_nH_{2n+2} + (1.5n + 0.5)O_2 \rightarrow nCO_2 + (n+1)H_2O$	—	—	$1.5n + 0.5$	$7.18n + 2.39$	—	128 to 127	n	$n + 1$	$\frac{44.01n}{14.026n + 2.016}$	$\frac{18.01(n+1)}{14.026n + 2.016}$
Ethylene	C_2H_4	$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O$	3.42	14.78	3.00	14.38	15.05	125	2.0	2.0	3.138	1.285
Propylene	C_3H_6	$C_3H_6 + 4.5O_2 \rightarrow 3CO_2 + 3H_2O$	3.42	14.78	4.50	21.53	15.05	125	3.0	3.0	3.138	1.285
Alkenes	C_nH_{2n}	$C_nH_{2n} + 1.5nO_2 \rightarrow nCO_2 + nH_2O$	3.42	14.78	$1.50n$	$7.18n$	15.05	125	n	n	3.138	1.285
Acetylene	C_2H_2	$C_2H_2 + 2.5O_2 \rightarrow 2CO_2 + H_2O$	3.07	13.27	2.50	11.96	17.53	103	2.0	1.0	3.834	0.692
Alkynes	C_nH_{2m}	$C_nH_{2m} + (n + 0.5m)O_2 \rightarrow nCO_2 + mH_2O$	—	—	$n + 0.5m$	$4.78n + 2.39m$	—	—	n	m	$\frac{22.005n}{6.005n + 1.008m}$	$\frac{9.008m}{6.005n + 1.008m}$
									SO_x	H_2O	SO_x	H_2O
Sulfur (to SO_2)	S	$S + O_2 \rightarrow SO_2$	1.00	4.31	b	b	—	—	$1.0SO_2$	—	1.998 (SO_2)	—
Sulfur (to SO_3)	S	$S + 1.5O_2 \rightarrow SO_3$	1.50	6.47	b	b	—	—	$1.0SO_3$	—	2.497 (SO_3)	—
Hydrogen sulfide	H_2S	$H_2S + 1.5O_2 \rightarrow SO_2 + H_2O$	1.41	6.08	1.50	7.18	—	125	$1.0SO_2$	1.0	1.880 (SO_2)	0.528

Adapted, in part, from *Gas Engineers Handbook* (1965).

[a]Atomic masses: H = 1.008, C = 12.01, O = 16.00, S = 32.06.

[b]Volume ratios are not given for fuels that do not exist in vapor form at reasonable temperatures or pressure.

[c]Dew point is determined from Figure 2.

Source: ASHRAE Handbook Fundamentals 2013, Chapter 28.2

Heating Equipment

- Burners
  - atmospheric injection, luminous flame, power burner
  - atmospheric vented, power-vented, direct vent (sealed)

- Residential Furnaces
  - horizontal, upflow, downflow
  - efficiencies
    - steady-state
    - utilization efficiency
    - annual fuel utilization efficiency

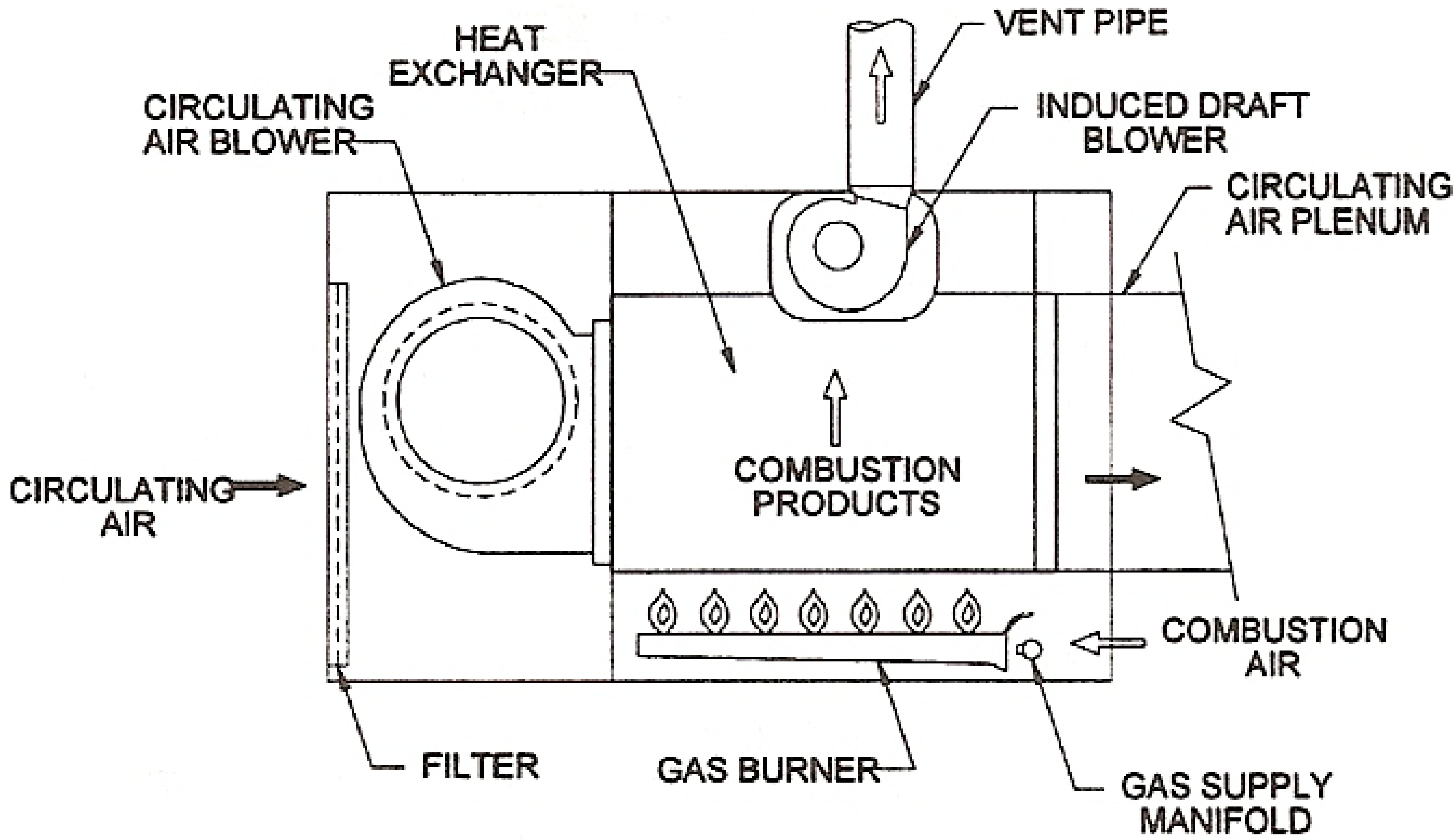

Fig. 19-3 Horizontal Forced Warm-Air Furnace

Source: Howell, Sauer, & Coad, Principles of Heating, Ventilating, & Air Conditioning, 1997, Chapter 19.6

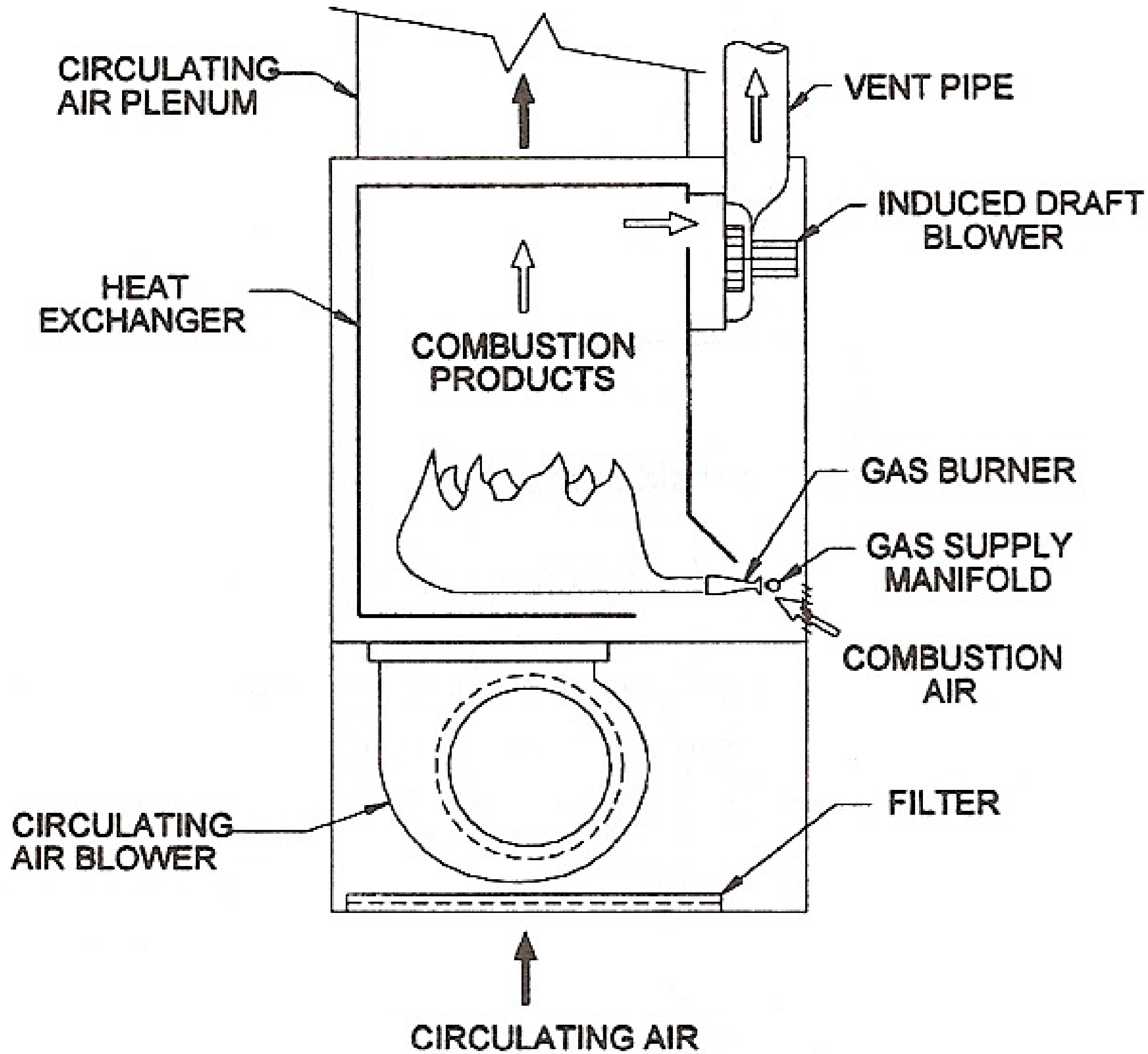

Fig. 19-4 Upflow Forced Warm-Air Furnace

Source: Howell, Sauer, & Coad, Principles of Heating, Ventilating, & Air Conditioning, 1997, Chapter 19.6

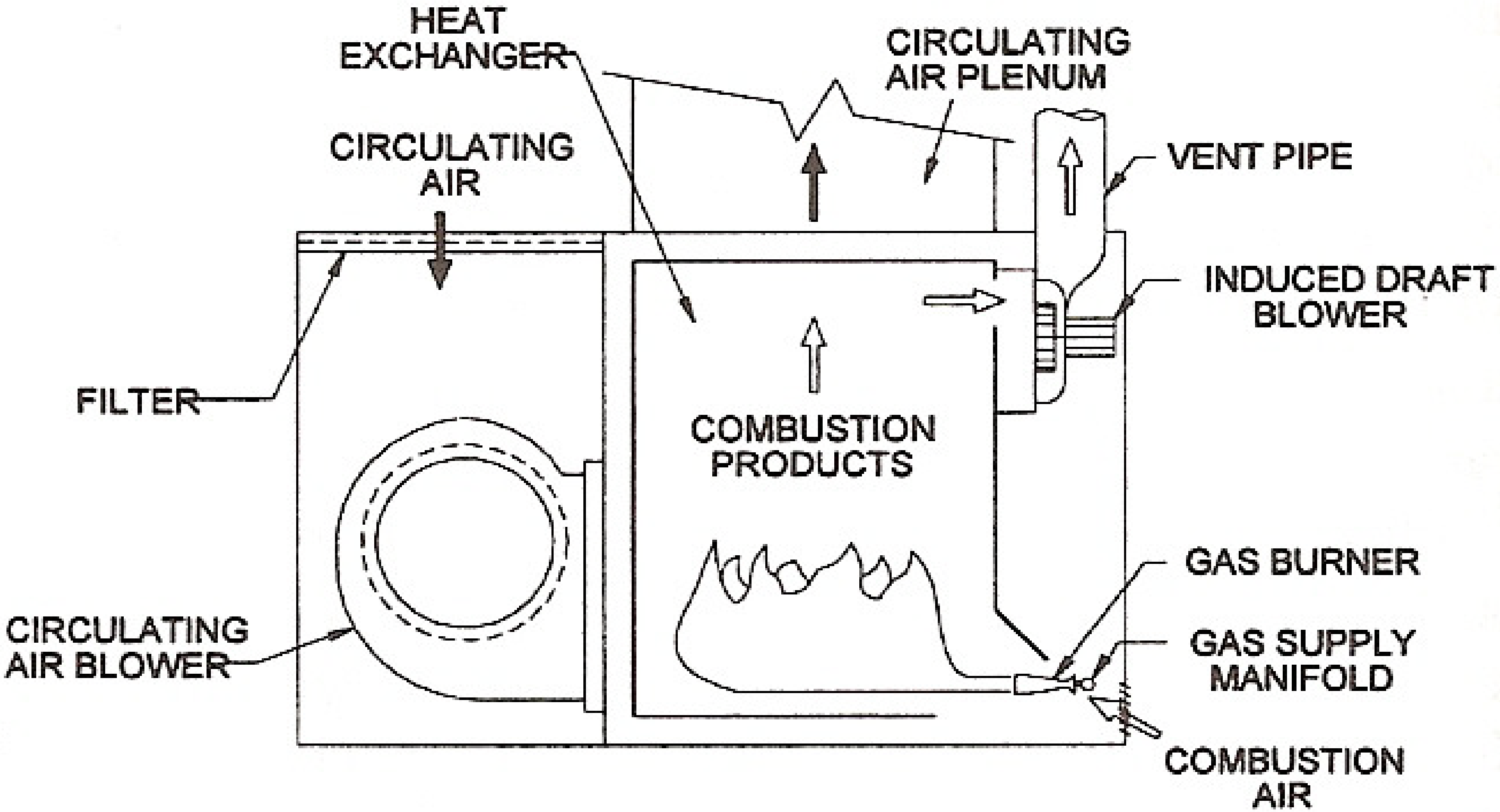

Fig. 19-5 Basement Forced Warm-Air Furnace

Source: Howell, Sauer, & Coad, Principles of Heating, Ventilating, & Air Conditioning, 1997, Chapter 19.6

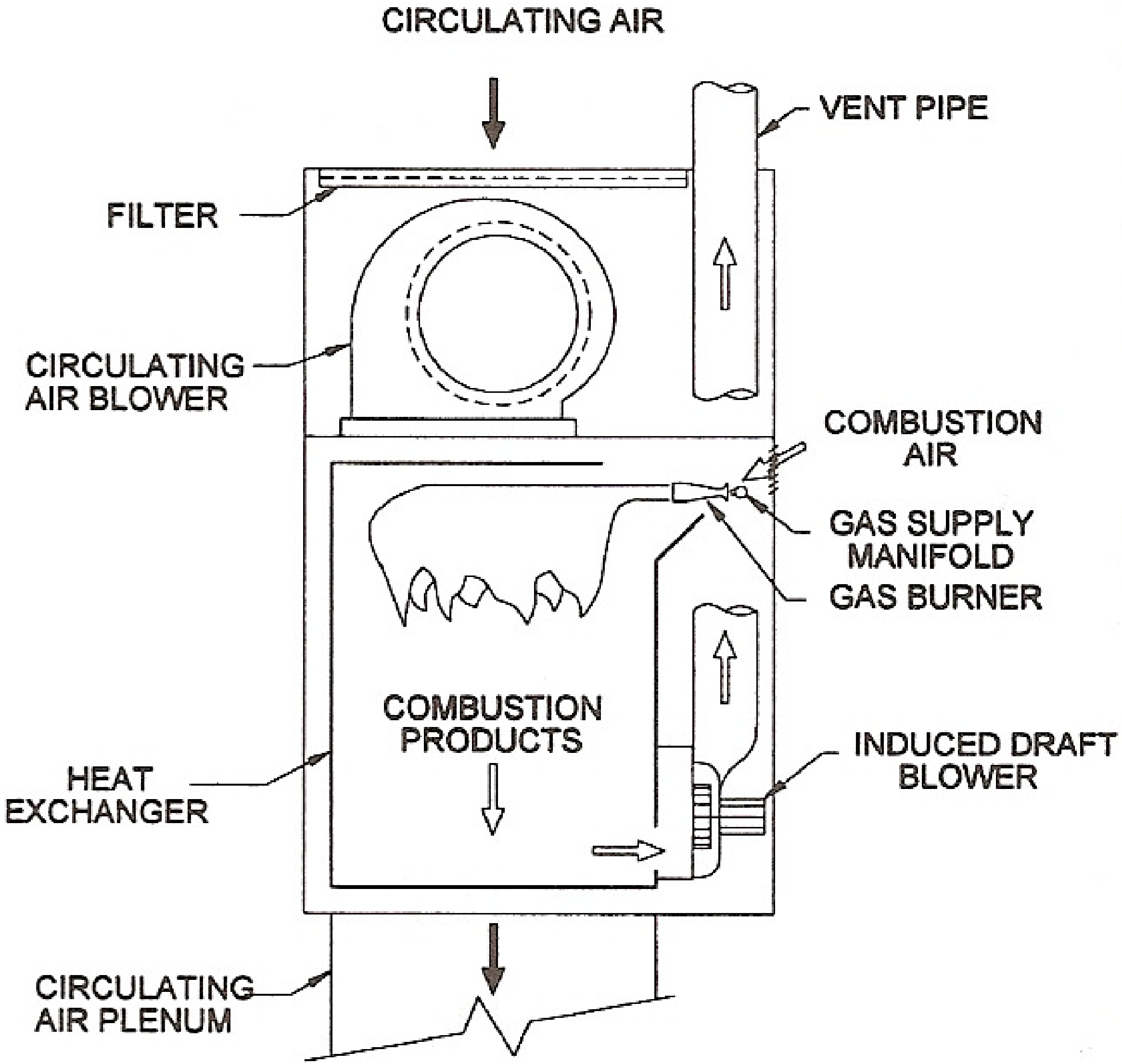

Fig. 19-6 Downflow (Counterflow) Warm-Air Furnace

Source: Howell, Sauer, & Coad, Principles of Heating, Ventilating, & Air Conditioning, 1997, Chapter 19.6

Heating Equipment

- Boilers
  - working temperature & pressure
  - efficiency
    - combustion efficiency
    - overall efficiency
- Terminal Units
  - radiator
  - convectors
  - baseboard
  - finned tubes
- Electric Heating

Terminal Units – Convectors/Radiators

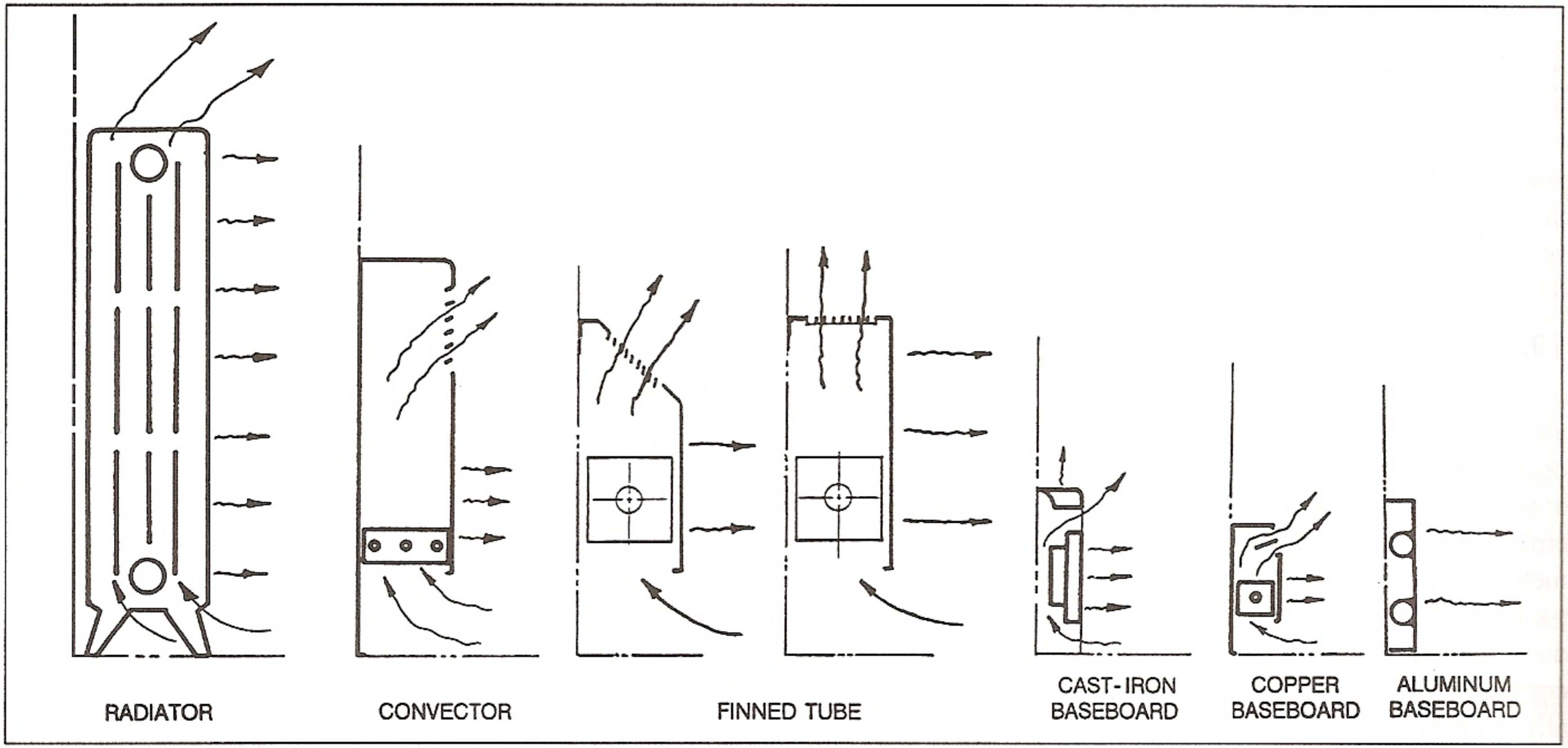

Fig. 19-11 Terminal Units

Source: Howell, Sauer, & Coad, Principles of Heating, Ventilating, & Air Conditioning, 1997, Chapter 19.13

Annual Fuel Utilization Efficiency

Table 19-5 AFUE Values of Various Furnaces Located in Conditioned Space

Type of Gas Furnace	AFUE, % Indoor	AFUE, % ICS[a]
1. Natural-draft with standing pilot	64.5	63.9
2. Natural-draft with intermittent ignition	69.0	68.5
3. Natural-draft with intermittent ignition and auto vent damper	78.0	68.5
4. Fan-assisted combustion with standing pilot or intermittent ignition	80.0	78.0
5. Same as 4, except with improved heat transfer	82.0	80.0
6. Direct vent with standing pilot, preheat	66.0	64.5
7. Direct vent, fan-assisted combustion, and intermittent ignition	80.0	78.0
8. Fan-assisted combustion (induced-draft)	80.0	78.0
9. Condensing	93.0+	91.0+
Type of Oil Furnace	**Indoor**	**ICS[a]**
1. Standard	71.0	69.0
2. Same as 1, with improved heat transfer	76.0	74.0
3. Same as 2, with auto vent damper	83.0	74.0
4. Condensing	91.0	89.0

[a]Isolated combustion system.

Source: Howell, Sauer, & Coad, Principles of Heating, Ventilating, & Air Conditioning, 1997, Chapter 19.7

In Summary

Questions and Discussion

Next Class

- Air Conditioning (Cooling)
  - Equipment
  - Systems
  - Efficiencies
  - Operations/Maintenance

- Readings
  - HF 20 (review only)
  - Air-Conditioning Handout