Louis D. Albright, 1990. Excerpts from Chapter 5, 8 and Appendices. In *Environment Control for Animals and Plants.* St. Joseph, Mich: American Society of Agricultural Engineers.

8-4.2. Airflow Through Hinged-Baffle and Center Ceiling Slotted Inlets. When the coefficient of discharge is known, airflow through inlets can be calculated if the static pressure difference and inlet areas are known. However, with slotted inlets, the coefficient of discharge is a function of the geometry of the inlet.

The following equations can be used to calculate volumetric airflow rates through slotted inlets:

a. Slotted inlet, baffle attached to the ceiling, airflow down the wall, cases (a) and (b) in Figure 8-8:

$$\dot{V} = 0.0012W^{0.98}\Delta P^{0.49} \qquad (8\text{-}27)$$

b. Slotted inlet, baffle attached to the wall, airflow across the ceiling, case (c) in Figure 8-8:

$$\dot{V} = 0.00071W^{0.98}\Delta P^{0.49} \qquad (8\text{-}28)$$

In Equations 8-27 and 8-28, $\dot{V}$ is in m^3/s per meter of inlet length (or m^2/s), W is the actual inlet width in mm, and ΔP is the static pressure difference across the inlet, in pascals. The two equations are based on experiments, thus the exponents of W and ΔP are not 1.0 and 0.5 as would be expected from basic principles. However, the differences are slight.

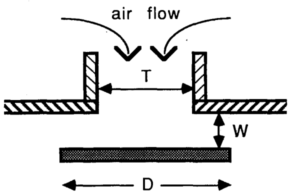
There is a major difference, however, in the magnitudes of airflows from the two inlets for the same inlet widths and static pressure difference. The coefficient of Equation 8-28 is only 59% of the coefficient of Equation 8-27. This is a significantly smaller coefficient of discharge and is a result of the way airflow within the inlet is restricted by the change of direction to flow along the ceiling. A less restrictive inlet could be designed by having fresh air come straight through the wall instead of over the top plate.

c. Center-ceiling slotted inlet, case (d) in Figure 8-8:

$$\dot{V} = 0.0013W^{0.98}\Delta P^{0.49}(D / T)^{0.08}\exp(-\ 0.867W / T) \qquad (8\text{-}29)$$

where, in this case, $\dot{V}$ includes airflow from both sides of the baffle, in m^3/s per meter of baffle length. Variables W and ΔP were previously defined, D is the width of the baffle board and T is the width of the slot through the ceiling.

It must be stressed that Equations 8-27 and 8-28 apply only when there is no airflow restriction of significance other than at the inlet formed by the baffle.



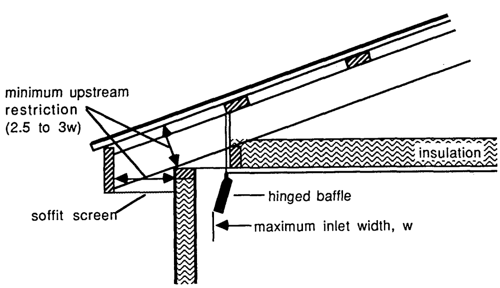
When air flows over the top of the outside wall (over the top plate), there must be no restriction at that point, for example. A rough rule is that upstream restrictions can be neglected if they are more than two and a half times as wide as the largest inlet width. For example, if a baffle is to operate to permit an inlet width as wide as 50 mm, the minimum upstream restriction must be 125 mm.

As livestock buildings become larger, animal stocking densities increase, more ventilation is required, and wider inlets are specified. Common construction techniques may inadvertently cause significant upstream restrictions and the ventilation system will never work as designed. It is the responsibility of the design engineer in such cases to ensure the design is specified to avoid such problems.

There are some limits in applying the center-ceiling inlet equation. When this style inlet is used, air enters first into the attic. A building design must ensure airflow into the attic will be unrestricted. In addition, Equation 8-29 was developed for restrictions

$$2 < D / T < 6, \text{ and}$$
$$0.109 < W / T < 1.46.$$

These ranges encompass typical design practices.



5-6.1. Carbon Dioxide Produced By Animals. Carbon dioxide is a by-product of metabolism, as is heat and moisture. The ratio between carbon dioxide production and total animal heat production is fixed by the biochemical processes of metabolism. Additional carbon dioxide may be produced from decomposition of wastes and digestive processes of ruminants, but such additional production is small compared to that respired by the animals.

One liter of carbon dioxide is produced, on the average, for every 24.6 kJ of total heat added to the environment by an animal. Total heat production of animals can be estimated using data in Appendix 5-1.

APPENDIX 6-1
DESIGN AIR TEMPERATURES FOR SELECTED STATIONS

	Winter Air Temp.		Summer Air Temp.		Summer MCWB		Summer DWB	
Station	99%	97.5%	1%	2.5%	1%	2.5%	1%	2.5%
Alabama								
Auburn	-8	-6	36	24	25	24	26	26
Huntsville	-12	-9	35	34	24	23	26	25
Mobile	-4	-2	35	34	25	25	27	26
Alaska								
Anchorage	-31	-28	20	19	15	14	16	15
Fairbanks	-46	-44	28	26	17	16	18	17
Juneau	-20	-17	23	21	16	14	16	15
Arizona								
Flagstaff	-19	-16	29	28	13	13	17	16
Phoenix	-1	1	43	42	22	22	24	24
Tucson	-2	0	40	39	19	19	22	22
Arkansas								
Fayetteville	-14	-11	36	34	24	23	25	24
Hot Springs	-8	-5	38	36	25	25	27	26
Little Rock	-9	-7	37	36	26	25	27	26
California								
Bakersfield	-1	0	40	38	21	21	23	22
Riverside	-2	0	38	37	20	19	22	22
Ukiah	-3	-2	37	35	21	20	21	20
Colorado								
Boulder	-17	-13	34	33	15	15	18	17
Denver	-21	-17	34	33	15	15	18	17
Fort Collins	-23	-20	34	33	15	15	18	17
Connecticut								
Bridgeport	-14	-13	30	29	23	22	24	23
New Haven	-16	-14	31	29	24	23	24	24
Waterbury	-20	-17	31	29	22	21	24	23
Delaware								
Dover	-12	-9	33	32	24	24	26	25
Wilmington	-12	-10	33	32	23	23	25	24
Florida								
Gainesville	-2	-1	35	34	25	25	27	26
Orlando	2	3	34	34	24	24	26	26
Tampa	2	4	33	33	25	25	26	26
Georgia								
Atlanta	-8	-6	34	33	23	23	25	24
Brunswick	-2	0	33	32	26	26	27	26
Columbus	-6	-4	35	34	24	24	26	26
Hawaii								
Hilo	16	17	29	28	23	22	24	23
Honolulu	17	17	31	30	23	23	24	24
Idaho								
Boise	-16	-12	36	34	18	18	20	19
Moscow	-22	-18	32	31	17	17	18	18
Twin Falls	-19	-17	37	35	16	16	18	17
Illinois								
Chicago	-21	-18	34	33	23	23	25	24
Peoria	-22	-20	33	32	24	23	26	24
Springfield	-19	-17	34	33	24	23	26	25
Indiana								
Evansville	-16	-13	35	34	24	24	26	26
Fort Wayne	-20	-17	33	32	23	22	25	24
Indianapolis	-19	-17	33	32	23	23	26	24
Iowa								
Ames	-24	-21	34	32	24	23	26	24
Des Moines	-23	-21	34	33	24	23	26	25
Ottumwa	-22	-20	34	33	24	23	26	25
Kansas								
Chanute	-16	-14	38	36	23	23	26	25
Hutchinson	-16	-13	39	37	22	22	25	24
Liberal	-17	-14	37	36	20	20	23	22
Kentucky								
Ashland	-15	-12	34	33	24	23	26	25
Lexington	-16	-13	34	33	23	23	25	24
Madisonville	-15	-12	36	34	24	24	26	26

Louisana								
Bogalusa	-4	-2	35	34	25	25	27	27
Minden	-7	-4	37	36	25	24	26	26
Shreveport	-7	-4	37	36	25	24	26	26
Maine								
Augusta	-22	-19	31	29	23	21	23	22
Caribou	-28	-25	29	27	21	19	22	21
Portland	-21	-18	31	29	22	22	23	22
Maryland								
Cumberland	-14	-12	33	32	24	23	25	24
Frederick	-13	-11	34	33	24	24	26	25
Salisbury	-11	-9	34	33	24	24	26	25
Massachusetts								
Fall River	-15	-13	31	29	22	22	23	23
Gloucester	-17	-15	32	30	23	22	24	23
Springfield	-21	-18	32	31	22	22	24	23
Michigan								
Alpena	-24	-21	32	29	21	21	23	22
Detroit	-16	-14	33	31	23	22	24	23
Lansing	-19	-17	32	31	23	22	24	23
Minnesota								
Duluth	-29	-27	29	28	21	20	22	21
Rochester	-27	-24	32	31	23	22	25	24
St. Cloud	-26	-24	33	31	23	22	24	23
Mississippi								
Biloxi	-2	-1	34	33	26	26	28	27
Jackson	-6	-4	36	35	24	24	26	26
Tupelo	-10	-7	36	34	25	25	27	26
Missouri								
Joplin	-14	-12	38	36	23	23	26	25
Rolla	-16	-13	34	33	25	24	26	25
Springfield	16	-13	36	34	23	23	26	25
Montana								
Bozeman	-29	-26	32	31	16	16	17	17
Cut Bank	-32	-29	31	29	16	16	18	17
Lewiston	-30	-27	32	31	17	16	18	17
Nebraska								
Fremont	-21	-19	37	35	24	23	26	25
Lincoln	-21	-19	37	35	24	23	26	25
Scottsbluff	-22	-19	35	33	18	18	21	20
Nevada								
Carson City	-16	-13	34	33	16	15	17	16
Ely	-23	-20	31	29	13	13	16	15
Las Vegas	-4	-2	42	41	19	18	22	21
New Hampshire								
Berlin	-26	-23	31	29	22	21	23	22
Concord	-22	-19	32	31	22	21	23	23
Portsmouth	-19	-17	32	29	23	22	24	23
New Jersey								
Paterson	-14	-12	34	33	23	23	25	24
Trenton	-12	-10	33	31	24	23	26	24
Vineland	-13	-12	33	32	24	23	26	24
New Mexico								
Albuquerque	-11	-9	36	34	16	16	19	18
Gallup	-18	-15	32	32	15	14	18	17
Roswell	-11	-8	38	37	19	19	22	21
New York								
Albany	-21	-18	33	31	23	22	24	23
Ithaca	-21	-18	31	29	22	22	23	23
Riverhead	-14	-12	30	28	22	22	24	23
North Carolina								
Raleigh	-9	-7	34	33	24	24	26	25
Rocky Mount	-8	-6	34	33	24	24	26	26
Wilmington	-5	-3	34	33	26	26	27	27
North Dakota								
Bismarck	-31	-28	35	33	20	20	23	22
Grand Forks	-32	-30	33	31	21	21	23	22
Minot	-31	-29	33	32	20	19	22	21
Ohio								
Cincinnati	-17	-14	33	32	23	22	25	24
Cleveland	-18	-15	33	32	23	23	25	24
Columbus	-18	-15	33	32	23	22	25	24
Oklahoma								
McAlester	-10	-7	37	36	23	23	25	24
Stillwater	-13	-11	38	36	23	23	25	24
Tulsa	-13	-11	38	37	23	24	26	26

Oregon								
Corvallis	-8	-6	33	32	19	19	21	19
Medford	-7	-5	37	34	20	19	21	20
Salem	-8	-5	33	31	20	19	21	20
Pennsylvania								
Erie	-16	-13	31	29	23	22	24	23
Harrisburg	-14	-12	34	33	24	23	25	24
Philadelphia	-12	-10	34	32	24	23	25	24
Rhode Island								
Providence	-15	-13	32	30	23	22	24	23
South Carolina								
Charleston	-4	-2	34	33	26	26	27	27
Columbia	-7	-4	36	35	24	24	26	26
Spartanburg	-8	-6	34	33	23	23	25	24
South Dakota								
Brookings	-27	-25	35	33	23	22	25	24
Peirre	-26	-23	37	35	22	22	24	23
Rapid City	-24	-22	35	33	19	18	22	21
Tennessee								
Athens	-11	-8	35	33	23	23	25	24
Knoxville	-11	-7	34	33	23	23	26	26
Memphis	-11	-8	37	35	25	24	27	26
Texas								
Amarillo	-14	-12	37	35	19	19	22	21
Brownsville	2	4	34	34	25	25	27	26
Plainview	-13	-11	37	36	20	20	22	22
Utah								
Logan	-19	-17	34	33	17	16	18	18
Provo	-17	-14	37	36	17	17	19	18
Richfield	-19	-15	34	33	16	16	19	18
Vermont								
Barre	-27	-24	29	27	22	21	23	22
Burlington	-24	-22	31	29	22	21	23	22
Rutland	-25	-22	31	29	22	21	23	22
Virginia								
Norfolk	-7	-6	34	33	25	24	26	26
Richmond	-10	-8	35	33	24	24	26	26
Roanoke	-11	-9	34	33	22	22	24	23
Washington								
Bellingham	-12	-9	27	25	19	18	20	18
Spokane	-21	-17	34	32	18	17	18	18
Yakima	-19	-15	36	34	18	18	20	19
West Virginia								
Clarksburg	-14	-12	33	32	23	23	24	24
Huntington	-15	-12	34	33	24	23	26	25
Wheeling	-17	-15	32	30	22	22	23	23
Wisconsin								
Ashland	-29	-27	29	28	21	20	22	21
Beloit	-22	-19	33	32	24	24	26	25
Madison	-24	-22	33	31	23	23	25	24
Wyoming								
Cheyenne	-23	-18	32	30	14	14	17	17
Rawlins	-24	-20	30	28	14	14	17	16
Sheridan	-26	-22	34	33	17	17	19	18
Alberta								
Calgary	-33	-31	29	27	17	16	18	17
Edmonton	-34	-32	29	28	19	18	20	19
Medicine Hat	-34	-31	34	32	19	18	21	20
British Columbia								
Dawson Creek	-38	-36	28	26	18	17	19	18
Trail	-21	-18	33	32	19	18	20	19
Vancouver	-9	-7	26	25	19	18	20	19
Manitoba								
Churchill	-41	-39	27	25	19	18	19	18
Dauphin	-35	-33	31	29	22	21	23	22
Winnipeg	-34	-33	32	30	23	22	24	23
New Brunswick								
Edmundston	-29	-27	31	28	21	20	23	22
Fredericton	-27	-24	32	29	22	21	23	22
Saint John	-24	-22	27	25	19	18	21	20
Newfoundland								
Gander	-21	-18	28	26	19	18	21	19
Goose Bay	-33	-31	29	27	19	18	20	19

Northwest Territories								
Inuvik	-49	-47	26	25	17	16	18	17
Nova Scotia								
Halifax	-17	-15	26	24	19	18	21	19
Sydney	-18	-16	28	27	21	20	22	21
Yarmouth	-15	-13	23	22	18	18	20	19
Ontario								
Hamilton	-19	-17	31	30	23	22	24	23
Sarnia	-18	-16	31	30	23	22	24	23
Timmins	-36	-34	31	29	21	20	22	21
Prince Edward Island								
Summerside	-22	-20	27	26	21	20	22	21
Quebec								
Hull	-28	-26	32	31	22	22	24	23
Montreal	-27	-23	31	29	23	22	24	23
Quebec	-28	-26	31	29	22	21	23	22
Saskatchewan								
Regina	-36	-34	33	31	21	20	22	21
Saskatoon	-37	-35	32	30	20	19	21	20
Yorkton	-37	-34	31	29	21	20	22	21
Yukon Territory								
Whitehorse	-43	-42	27	25	15	14	16	15

a. Mean Coincident Wet Bulb Temperature
b. Design Wet Bulb Temperature

Data abstracted from the ASHRAE Handbook of Fundamentals

APPENDIX 3-2
DESIGN HEAT TRANSMISSION COEFFICIENTS
Taken from the 1985 ASHRAE Handbook of Fundamentals, American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta GA. (Used by permission.)

Thermal Properties of Typical Building and Insulating Materials—Design Values[a]

Description	Density kg/m³	Conductivity λ W/m•°C	Conductance (C) W/m²•°C	Resistance (R) Per meter thickness (1/λ) m•°C/W	Resistance (R) For thickness listed (1/C) m²•°C/W	Specific Heat kJ/(kg•°C)
BUILDING BOARD						
Boards, Panels, Subflooring, Sheathing						
Woodboard Panel Products						
Asbestos-cement board	1920	0.576	—	1.74	—	1.01
Asbestos-cement board ... 3.18 mm	1920	—	187.4	—	0.005	
Asbestos-cement board ... 6.35 mm	1920	—	93.72	—	0.011	
Gypsum or plaster board ... 9.53 mm	800	—	17.61	—	0.056	1.09
Gypsum or plaster board ... 12.70 mm	800	—	12.61	—	0.079	
Gypsum or plaster board ... 15.88 mm	800	—	10.11	—	0.099	
Plywood (Douglas Fir)	544	0.115	—	8.68	—	1.22
Plywood (Douglas Fir) ... 6.35 mm	544	—	18.18	—	0.055	
Plywood (Douglas Fir) ... 9.53 mm	544	—	12.10	—	0.083	
Plywood (Douglas Fir) ... 12.70 mm	544	—	9.09	—	0.11	
Plywood (Douglas Fir) ... 15.88 mm	544	—	7.33	—	0.14	
Plywood or wood panels ... 19.05 mm	544	—	6.08	—	0.16	1.22
Vegetable Fiber Board						
Sheathing, regular density ... 12.70 mm	288	—	4.32	—	0.23	1.30
... 19.84 mm	288	—	2.78	—	0.36	
Sheathing intermediate density ... 12.70 mm	352	—	4.66	—	0.21	1.30
Nail-base sheathing ... 12.70 mm	400	—	5.00	—	0.20	1.30
Shingle backer ... 9.53 mm	288	—	6.02	—	0.17	1.30
Shingle backer ... 7.94 mm	288	—	7.27	—	0.14	
Sound deadening board ... 12.70 mm	240	—	4.20	—	0.24	1.26
Tile and lay-in panels, plain or acoustic	288	0.058	—	17.35	—	0.59
... 12.70 mm	288	—	4.54	—	0.22	
... 19.05 mm	288	—	3.01	—	0.33	
Laminated paperboard	480	0.072	—	13.88	—	1.38
Homogeneous board from repulped paper	480	0.072	—	13.88	—	1.17
Hardboard						
Medium density	800	0.105	—	9.51	—	1.30
High density, service temp. service underlay	880	0.118	—	8.47	—	1.34
High density, std. tempered	1008	0.144	—	6.94	—	1.34
Particleboard						
Low density	592	0.078	—	12.84	—	1.30
Medium density	800	0.135	—	7.36	—	1.30
High density	1000	0.170	—	5.90	—	1.30
Underlayment ... 15.88 mm	640	—	6.93	—	0.14	1.22
Wood subfloor ... 19.05 mm		—	6.02	—	0.17	1.38
BUILDING MEMBRANE						
Vapor—permeable felt	—	—	94.86	—	0.011	
Vapor—seal, 2 layers of mopped 0.73 kg/m² felt	—	—	47.43	—	0.021	
Vapor—seal, plastic film	—	—	—	—	Negl.	
FINISH FLOORING MATERIALS						
Carpet and fibrous pad	—	—	2.73	—	0.37	1.42
Carpet and rubber pad	—	—	4.60	—	0.22	1.38
Cork tile ... 3.18 mm	—	—	20.45	—	0.049	2.01
Terrazzo ... 25.40 mm	—	—	71.00	—	0.014	0.80
Tile—asphalt, linoleum, vinyl, rubber	—	—	113.6	—	0.009	1.26
vinyl asbestos						1.01
ceramic						0.80
Wood, hardwood finish ... 19.05 mm			8.35		0.12	
INSULATING MATERIALS						
Blanket and Batt[b]						
Mineral Fiber, fibrous form processed from rock, slag, or glass						
approx.[c] 76.2–101.6 mm	4.8-32.0	—	0.52	—	1.94[b]	
approx.[c] 88.9 mm	4.8-32.0		0.44	—	2.29[b]	
approx.[c] 139.7–165.1 mm	4.8-32.0	—	0.30	—	3.34[b]	
approx.[c] 152.4–177.8 mm	4.8-32.0		0.26		3.87[b]	
approx.[c] 215.9–228.6 mm	4.8-32.0		0.19		5.28[b]	
approx. 304.8 mm	4.8-32.0	—	0.15		6.69[b]	

Thermal Properties of Typical Building and Insulating Materials—Design Values[a]

Description	Density kg/m³	Conductivity (λ) W/m•°C	Conductance (C) W/m²•°C	Resistance (R) Per meter thickness	Resistance (R) For thickness listed	Specific Heat kJ/(kg•°C)
Board and Slabs						
Cellular glass	136	0.050	—	*19.85*	—	0.75
Glass fiber, organic bonded	64–144	0.036	—	*27.76*	—	0.96
Expanded perlite, organic bonded	16.0	0.052	—	*19.29*	—	1.26
Expanded rubber (rigid)	72.0	0.032	—	*31.58*	—	1.68
Expanded polystyrene extruded						
Cut cell surface	28.8	0.036	—	*27.76*	—	1.22
Smooth skin surface	28.8–56.0	0.029	—	*34.70*	—	1.22
Expanded polystyrene, molded beads	16.0	0.037	—	*23.25*	—	—
	20.0	0.036	—	*27.76*	—	—
	24.0	0.035	—	*28.94*	—	—
	28.0	0.035	—	*28.94*	—	—
	32.0	0.033	—	*30.19*	—	—
Cellular polyurethane[c] (R-11 exp.)(unfaced)	24.0	0.023	—	*43.38*	—	1.59
Foil-faced, glass fiber-reinforced cellular						
Polyisocyanurate (R-11 exp.)[d]	32.0	0.020	—	*49.97*	—	0.92
Nominal 12.70 mm		—	1.58	—	*0.63*	
Nominal 25.40 mm		—	0.79	—	*1.27*	
Nominal 50.80 mm		—	0.39	—	*2.53*	
Mineral fiber with resin binder	240	0.042	—	*23.94*	—	0.71
Mineral fiberboard, wet felted						
Core or roof insulation	256–272	0.049	—	*20.40*	—	
Acoustical tile	288	0.050	—	*19.85*	—	0.80
Acoustical tile	336	0.053	—	*18.74*	—	
Mineral fiberboard, wet molded						
Acoustical tile[e]	368	0.060	—	*16.52*	—	0.59
Wood or cane fiberboard						
Acoustical tile[e] ... 12.70 mm	—	—	4.54	—	*0.22*	1.30
Acoustical tile[e] ... 19.05 mm	—	—	3.01	—	*0.33*	
Interior finish (plank, tile)	240	0.050	—	*19.85*	-	1.34
Cement fiber slabs (shredded wood with Portland cement binder	400–432	0.072–0.070	—	*13.88-13.12*	-	—
Cement fiber slabs (shredded wood with magnesia oxysulfide binder)	352	0.082	—	*12.15*	-	1.30
LOOSE FILL						
Cellulosic insulation (milled paper or wood pulp)	36.8–51.2	0.039–0.046	—	*25.68–21.72*	—	1.38
Sawdust or shavings	128–240	0.065	—	*15.41*	—	1.38
Wood fiber, softwoods	32.0–56.0	0.043	—	*23.11*	—	1.38
Perlite, expanded						
	32.0–65.6	0.039–0.045		*25.68–22.90*		
	65–118	0.045–0.052		*22.90–19.43*		
	118–176	0.052–0.060		*19.43–16.66*		
Mineral fiber (rock, slag or glass)						
approx. 95.3–127.0 mm	9.6–32.0	—	—		1.94	0.71
approx. 165.1–222.3 mm	9.6–32.0	—	—		3.34	
approx. 190.5–254.0 mm	9.6–32.0	—	—		3.87	
approx. 260.4–349.3 mm	9.6–32.0	—	—		5.28	
Mineral fiber (rock, slag or glass)						
approx. 83.8 mm (closed sidewall application)	32.0–56.0	—	—	—	2.46	
Vermiculite, exfoliated	112–131	0.068	—	*14.78*	—	1.34
	64.0–96.0	0.063	—	*15.75*	—	
FIELD APPLIED						
Polyurethane foam	24.0–40.0	0.023–0.026	—	43.38–36.50	—	
Ureaformaldehyde foam	11.2–25.6	0.032–0.040	—	24.78–31.58	—	
Spray cellulosic fiber base	32.0–96.0	0.035–0.043	—	23.11–28.94	—	
PLASTERING MATERIALS						
Cement plaster, sand aggregate	1865	0.720	—	*1.39*	—	0.84
Sand aggregate ... 9.53 mm	—	—	75.54	—	*0.014*	0.84
Sand aggregate ... 19.05 mm	—	—	37.83	—	*0.026*	0.84
Gypsum plaster:						
Lightweight aggregate ... 12.70 mm	720	—	17.72	—	*0.056*	
Lightweight aggregate ... 15.88 mm	720	—	15.17	—	*0.069*	
Lightweight agg. on metal lath ... 19.05 mmin.	—	—	12.10	—	*0.083*	
Perlite aggregate	720	0.216	—	*4.65*	—	1.34

Thermal Properties of Typical Building and Insulating Materials—Design Values[a]

Description	Density kg/m^3	Conductivity (λ) W/m·°C	Conductance (C) W/m^2·°C	Resistance (R) Per meter thickness	Resistance (R) For thickness listed	Specific Heat kJ/(kg·°C)
PLASTERING MATERIALS						
Sand aggregate	1680	0.806	—	*1.25*	—	0.84
Sand aggregate 12.70 mm	1680	—	63.05	—	*0.016*	
Sand aggregate 15.88 mm	1680	—	51.69	—	*0.019*	
Sand aggregate on metal lath 19.05 mm	—	—	43.74	—	*0.023*	
Vermiculite aggregate	720	0.245	—	*4.09*	—	
MASONRY MATERIALS						
Concretes						
Cement mortar	1856	0.720	—	*1.39*	—	
Gypsum-fiber concrete 87.5% gypsum, 12.5% wood chips	816	0.239	—	*4.16*	—	0.88
Lightweight aggregates including ex-	1920	0.749	—	*1.32*	—	
panded shale, clay or slate; expanded	1600	0.518	—	*1.94*	—	
slags; cinders; pumice; vermiculite;	1280	0.360	—	*2.78*	—	
also cellular concretes	960	0.245	—	*4.09*	—	
	640	0.166	—	*5.97*	—	
	480	0.130	—	*7.70*	—	
	320	0.101		*9.92*		
Perlite, expanded	640	0.134		*7.50*		
	480	0.102		*9.79*		
	320	0.072		*13.88*		1.34
Sand and gravel or stone aggregate (oven dried)	2240	1.296	—	*0.76*		0.92
Sand and gravel or stone aggregate (not dried)	2240	1.728	—	*0.56*		
Stucco	1856	0.720	—	*1.39*		
MASONRY UNITS						
Brick, common[f]	1920	0.720	—	*1.39*	—	0.80
Brick, face[f]	2080	1.296	—	*0.76*	—	
Clay tile, hollow:						
1 cell deep 76.2 mm	—	—	7.10	—	*0.14*	0.88
1 cell deep 101.6 mm	—	—	5.11	—	*0.20*	
2 cells deep 152.4 mm	—	—	3.75	—	*0.27*	
2 cells deep 203.2 mm	—	—	3.07	—	*0.33*	
2 cells deep 254.0 mm	—	—	2.56	—	*0.39*	
3 cells deep 304.8 mm	—	—	2.27	—	*0.44*	
Concrete blocks, three oval core:						
Sand and gravel aggregate 101.6 mm	—	—	7.95	—	*0.12*	0.92
203.2 mm	—	—	5.11	—	*0.20*	
304.8 mm	—	—	4.43	—	*0.23*	
Cinder aggregate 76.2 mm	—	—	6.59	—	*0.15*	0.88
101.6 mm	—	—	5.11	—	*0.20*	
203.2 mm	—	—	3.29	—	*0.30*	
304.8 mm	—	—	3.01	—	*0.33*	
Lightweight aggregate 76.2 mm	—	—	4.49	—	*0.22*	0.88
expanded shale, clay, slate 101.6 mm	—	—	3.81	—	*0.26*	
or slag; pumice 203.2 mm	—	—	2.84	—	*0.35*	
304.8 mm	—	—	2.50	—	*0.40*	
Concrete blocks, rectangular core.[g]						
Sand and gravel aggregate						
2 core,[h] 203.2 mm, 16.3 kg	—	—	5.45	—	*0.18*	0.92
Same with filled cores[i]	—	—	2.95	—	*0.34*	0.92
Lightweight aggregate (expanded shale, clay, slate or slag, pumice):						
3 core,[h] 152.4 mm, 8.6 kg	—	—	3.46	—	*0.29*	0.88
Same with filled cores[i]	—	—	1.87	—	*0.53*	
2 core,[h] 203.2 mm, 10.9 kg	—	—	2.61	—	*0.38*	
Same with filled cores[i]	—	—	1.14	—	*0.89*	
3 core,[h] 304.8 mm, 17.3 kg	—	—	2.27	—	*0.44*	
Same with filled cores[i]	—	—	0.97	—	*1.02*	
Stone, lime or sand	—	1.800	—	*0.56*	—	0.80
Gypsum partition tile:						
76.2 • 304.8 • 762.0 mm, solid	—	—	4.49	—	*0.22*	*0.80*
76.2 • 304.8 • 762.0 mm, 4-cell	—	—	4.20	—	*0.24*	
101.6 • 304.8 • 762.0 mm, 3-cell	—	—	3.41	—	*0.29*	

Thermal Properties of Typical Building and Insulating Materials—Design Values[a]

Description	Density kg/m³	Conductivity λ W/m• °C	Conductance (C) W/m• °C	Resistance (R) Per meter thickness (1/λ) m• °C/W	Resistance (R) For thickness listed (1/C) m² • °C/W	Specific Heat kJ/ (kg • °C)
METALS (See Chapter 39, Table 3)						
ROOFING						
Asbestos-cement shingles	1920	—	27.04	—	*0.037*	1.01
Asphalt roll roofing	1120	—	36.92	—	*0.026*	1.51
Asphalt shingles	1120	—	12.89	—	*0.077*	1.26
Built-up ... 9.53 mm	1120	—	17.04	—	*0.058*	1.47
Slate ... 12.70 mm	—	—	113.6	—	*0.009*	1.26
Wood shingles, plain and plastic film faced	—	—	6.02	—	*0.17*	1.30
SIDING MATERIALS (on flat surface)						
Shingles						
Asbestos-cement	1920	—	26.98	—	*0.037*	
Wood, 406.4 mm, 190.5 mm exposure	—	—	6.53	—	*0.15*	1.30
Wood, double, 406.4 mm, 304.8 mm exposure	—	—	4.77	—	*0.21*	1.17
Wood, plus insul. backer board, 7.94 mm	—	—	4.03	—	*0.25*	1.30
Siding						
Asbestos-cement, 6.35 mm, lapped	—	—	27.04	—	*0.037*	1.01
Asphalt roll siding	—	—	36.92	—	*0.026*	1.47
Asphalt insulating siding (12.70 mm bed.)	—	—	3.92	—	*0.26*	1.47
Hardboard siding, 11.11 mm	640	0.215	—	*4.65*		1.17
Wood, drop, 25.4 • 203.2 mm	—	—	7.21	—	*0.14*	1.17
Wood, bevel, 12.7 • 203.2 mm, lapped	—	—	6.99	—	*0.14*	1.17
Wood, bevel, 19.1 • 254.0 mm, lapped	—	—	5.40	—	*0.18*	1.17
Wood, plywood, 9.53 mm, lapped	—	—	9.03	—	*0.10*	1.22
Aluminum or Steel[j], over sheathing						
Hollow-backed	—	—	9.14	—	*0.11*	1.22
Insulating-board backed nominal 9.53 mm	—	—	3.12	—	*0.32*	1.34
Insulating-board backed nominal 9.53 mm, foil backed			1.93		*0.52*	
Architectural glass	—	—	56.80	—	*0.018*	0.84
WOODS (12% Moisture Content)[k,l]						
Hardwoods						1.63
Oak	659-749	0.161-0.180	—	*6.18-5.55*	—	
Birch	682-726	0.167-0.176	—	*6.04-5.69*	—	
Maple	637-704	0.157-0.171	—	6.52-6.11	—	
Ash	614-670	0.153-0.164	—	6.52-6.11	-	
Softwoods						1.63
Southern Pine	570-659	0.144-0.161	—	6.94-6.18	—	
Douglas Fir-Larch	536-581	0.137-0.145	—	7.36-6.87	—	
Southern Cypress	502-514	0.130-0.132	—	7.70-7.56	—	
Hem-Fir, Spruce-Pine-Fir	392-502	0.107-0.130	—	9.37-7.70	—	
West Coast Woods, Cedars	347-502	0.098-0.130	—	10.27-7.70	—	
California Redwood	392-448	0.107-0.118	—	9.37-8.47	—	

Notes

[a]Except where otherwise noted, all values are for a mean temperature of 23.9°C. Representative values for dry materials, selected by ASHRAE TC 4.4, are intended as design (not specification) values for materials in normal use. Insulation materials in actual service may have thermal values that vary from design values depending on their in-situ properties (e.g., density and moisture content). For properties of a particular product, use the value supplied by the manufacturer or by unbiased tests.

[b]Does not include paper backing and facing, if any. Where insulation forms a boundary (reflective or otherwise) of an air space, see Tables 1, 2A and 2B for the insulating value of an air space with the appropriate effective emittance and temperature conditions of the space.

[c]Values are for aged, unfaced, board stock. For change in conductivity with age of expanded urethane, see Chapter 20, Factors Affecting Thermal Conductivity.

[d]Time-aged values for board stock with gas-barrier quality (0.025 mm thickness or greater) aluminum foil facers on two major surfaces.

[e]Insulating values of acoustical tile vary, depending on density of the board and on type, size and depth of perforations.

[f]Face brick and common brick do not always have these specific densities. When density differs from that shown, there is a change in thermal conductivity.

[g]Data on rectangular core concrete blocks differ from the above data on oval core blocks, due to core configuration, different mean temperatures, and possibly differences in unit weights. Weight data on the oval core blocks tested are not available.

[h]Weights of units approximately 193.7 mm high and 400.1 mm long. These weights are given as a means of describing the blocks tested, but conductance values are all for 0.093m² of area.

[i]Vermiculite, perlite, or mineral wool insulation. Where insulation is used, vapor barriers or other precautions must be considered to keep insulation dry.

[j]Values for metal siding applied over flat surfaces vary widely, depending on amount of ventilation of air space beneath the siding; whether air space is reflective or nonreflective; and on thickness, type, and application of insulating backing-board used. Values given are averages for use as design guides, and were obtained from several guarded hotbox tests (ASTM C236) or calibrated hotbox (BSS 77) on hollow-backed types and types made using backing-boards of wood fiber, foamed plastic, and glass fiber. Departures of±50% or more from the values given may occur.

[k]Forest Products Laboratory Wood Handbook, U.S. Dept. of Agriculture #72, 1974, Tables 3 and 4.

[l]L. Adams: Supporting cryogenic equipment with wood (*Chemical Engineering*, May 17, 1971).

The next zone, 3, forms the major part of the jet. It is the zone of fully established, turbulent flow where the maximum jet velocity slows as the inverse of the square root of distance from the beginning of the zone. This zone continues until the maximum jet speed is reduced to approximately 0.25 m/s. The zone can be up to 100 jet diameters long and is the zone of primary engineering importance. The distance at which zone 3 ends is termed the "throw" of the jet.

After zone 3, momentum within the jet is sufficiently small that eddies in the air within the ventilated space overwhelm the jet, the velocity profile degenerates, and the jet disappears. This is zone 4 and is limited to a distance of only a few (local) jet diameters.

Detailed equations to calculate the decay of the maximum velocity of wall jets can be found in the *ASHRAE Handbook of Fundamentals*, for example. For practical design calculations related to the type of wall jets used to ventilate agricultural buildings, the following equation has been found to be adequate from the inlet to the throw of a plane wall jet:

$$v_{max} = 2.76 v_{inlet} (x/W)^{-0.5}, \tag{8-9}$$

where v_{inlet} is the jet velocity as it passes through the inlet of width W, x is the downstream distance, and v_{max} is the maximum velocity within the jet's velocity profile at x.

$$q_s + q_m + q_{so} + q_h + q_{vi} = q_w + q_f + q_e + q_{vo} \quad (5\text{-}1)$$

Mass balance. A simple mass balance for the same airspace is shown in the sketch of Figure 5-2. The same control volume is used as for the sensible heat balance.

The mass flow terms are:

m_p: the rate the material of interest (water vapor, carbon dioxide, etc.) is produced within the space.

m_{vi}: the rate at which the material of interest is carried into the airspace by ventilation air.

m_{vo}: the rate at which the material of interest is carried out of the airspace by ventilation air.

Several assumptions are contained within the sketch in Figure 5-2. Mass transfer by diffusion through the structural cover and floor is assumed to be sufficiently slow as to be negligible. The sources of the material of interest may be many but are shown as a collective whole. The material of interest is assumed not to undergo a transformation within the space to another material [such as the conversion of latent heat (in humidity) to sensible heat by condensation to form fog]. The only removal mechanism is ventilation; for example, dust in the air does not settle out onto the floor or adhere to the walls. Air in the space is well mixed.

The steady-state mass balance for Figure 5-2 is

$$m_p + m_{vi} = m_{vo}. \quad (5\text{-}2)$$

Individual terms of the energy and mass balances will now be examined in detail.

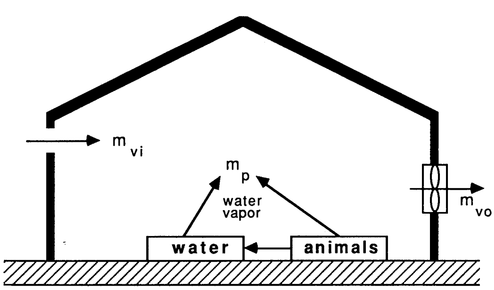


Figure 5-2. Mass balance for a single airspace.

5-2. Components of the Sensible Energy Balance

The energy balance can be used for many purposes. Heating or cooling required to maintain a predetermined air temperature can be calculated. The ventilation rate required to maintain design conditions can be found. The indoor air temperature in response to imposed conditions can be determined. The amount of insulation needed to limit heating may be of interest. However, before those calculations are possible, the components of the energy balance must be quantified. Some of the components have been discussed previously – some have not.

5-2.1. Sensible Heat Produced by Animals, q_s. Mammals are homeothermic creatures. That is, they attempt to maintain constant body temperatures (a state of homeothermy). Body temperatures are generally above those of the ambient air.

While poultry body temperatures are approximately 41 C, mammals of commercial importance in agriculture maintain body temperatures in the vicinity of 38 C. Internal physiological processes which maintain constant conditions are extremely complex and together are a condition termed "homeostasis". More complete descriptions of animal physiology and homeothermy can be found, for example, in Hellickson and Walker (1983), Esmay and Dixon (1986), and especially Clark (1981) and Curtis (1983).

The first priority of homeostasis is to maintain body temperature. If there is not sufficient feed to support body temperature, growth, and production, then production and growth slow. During cold weather when more heat is needed to maintain body temperature, more feed is eaten if available. In extreme cold, growth may become negative when fat is metabolized to maintain body temperature.

Sensible heat production is a by-product of maintenance, growth, and production; if conditions are extremely hot, production (e.g., milk or eggs) and feed intake are reduced to limit the quantity of sensible heat which must be expelled to the environment.

However, good agricultural practices mean ambient conditions should be regulated and sufficient food provided to the animals so all three functions can be supported with something approaching an optimal level. The temperature zone where this is possible is called the "comfort zone"; conditions outside the zone characterize "thermal stress".

Ambient thermal environment significantly affects animals, and the animals housed within a building significantly affect the environment within the building. A focus on the second effect is required to solve the energy balance in Equation 5-1.

5-5. Uses of the Mass Balance, Moisture

In most design situations, outdoor conditions are chosen based on design weather data and indoor conditions are specified based on the needs of the animals or plants within the space. If the moisture production rate, m_{water}, is known, the ventilation rate required to maintain indoor humidity at its design value may be calculated using a rearrangement of the mass balance, Equation 5-2.

In practical terms, this calculation provides an estimate of the minimum ventilation rate. If a higher ventilation rate is necessary to maintain conditions at the design temperature, a humidity lower than design conditions will result.

$$m_{air} = m_{water} / (W_i - W_0). \qquad (5\text{-}16)$$

This presents no problem, for design humidity conditions are usually chosen to be the maximum desired. If an exact humidity level is desired, irrespective of the ventilation needed for temperature control, moisture must be added to or removed from the air by mechanical means (a humidifier or a dehumidifier) .

Sensible energy balance. A simple set of sensible energy transfers for a single airspace building is shown in the sketch of Figure 5-1.

The energy flow terms are:

q_s: sensible heat gain from animals (or people) within the airspace.

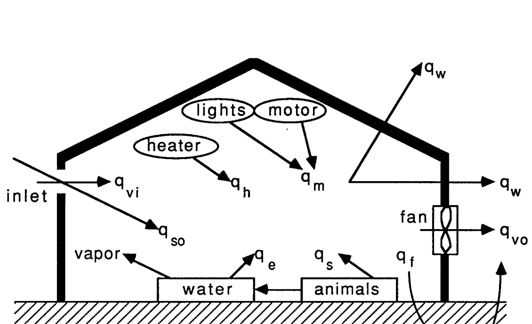


Figure 5-1. Contributors to a sensible energy balance in an animal housing building.

q_m: sensible heat gain from "mechanical" sources such as motors and lights. Such sources are usually electrical devices, and the heat gain is from conversion of electrical energy to sensible heat.

q_{so}: sensible heat gain from the sun. This can be gain through windows in a barn, and be relatively small, or it can be solar gain into a greenhouse and dominate all other heat gains.

q_h: sensible heat gain from a heating system.

q_{vi}: the sensible heat contained in the ventilation air entering the space referenced to some temperature datum. The datum is immaterial as, eventually, only the difference of sensible heat contents of the entering and exiting airstreams will be considered.

q_w: the transfer of sensible heat through the structural cover of the building; i.e., walls, ceiling, windows, doors, etc.

q_f: sensible heat transfer to the floor of the building primarily at the perimeter. It will be assumed that heat exchange with the floor in the interior of the building is relatively insignificant.

q_e: the rate of conversion of sensible heat to latent heat within the airspace. For example, evaporation of water from the floor of a barn or transpiration and evaporation of water from plants in a greenhouse are conversions of sensible to latent heat.

q_{vo}: the sensible heat contained in the ventilation air leaving the space referenced to the same temperature datum as q_{vi}.

The control volume for the energy balance is the air within the space bounded by the walls, floor, ceiling, and imaginary planes at the ventilation inlets and outlets. We need not specify the type of ventilation, or if total ventilation has a component of air infiltration through cracks. The arrows in Figure 5-1 indicate the assumed directions of heat transfers. The assumed directions need not be fixed, as long as the resulting energy balance is written to agree with the directions.

The general form of an energy balance for a control volume is

Gains - Losses = Change of Storage,

and if conditions are steady-state, there is no change of storage.

The steady-state sensible energy balance for Figure 5-1 rearranged in the form

Gains = Losses is

$$q_s + q_m + q_{so} + q_h + q_{vi} = q_w + q_f + q_e + q_{vo} \quad (5\text{-}1)$$

Mass balance. A simple mass balance for the same airspace is shown in the sketch of Figure 5-2. The same control volume is used as for the sensible heat balance.

The mass flow terms are:

m_p: the rate the material of interest (water vapor, carbon dioxide, etc.) is produced within the space.

m_{vi}: the rate at which the material of interest is carried into the airspace by ventilation air.

m_{vo}: the rate at which the material of interest is carried out of the airspace by ventilation air.

Several assumptions are contained within the sketch in Figure 5-2. Mass transfer by diffusion through the structural cover and floor is assumed to be sufficiently slow as to be negligible. The sources of the material of interest may be many but are shown as a collective whole. The material of interest is assumed not to undergo a transformation within the space to another material [such as the conversion of latent heat (in humidity) to sensible heat by condensation to form fog]. The only removal mechanism is ventilation; for example, dust in the air does not settle out onto the floor or adhere to the walls. Air in the space is well mixed.

The steady-state mass balance for Figure 5-2 is

$$m_p + m_{vi} = m_{vo}. \quad (5\text{-}2)$$

Individual terms of the energy and mass balances will now be examined in detail.

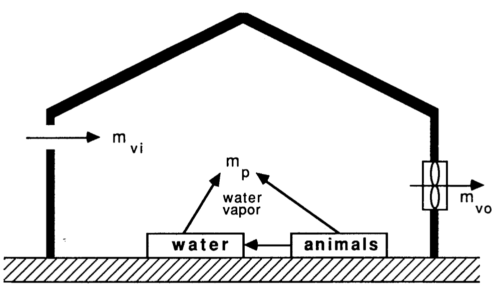


Figure 5-2. Mass balance for a single airspace.

Equation 5-1 can be rewritten in the following form:

$$q_s + q_m + q_{so} + q_h = \Sigma UA(t_i - t_o) + FP(t_i - t_o) + 1006\rho\dot{V}(t_i - t_o) + q_e. \qquad (5\text{-}10)$$

The addition of solar heat, q_{so}, is kept in symbol form and would be calculated separately as the product of transmittance, glazing area, and solar intensity; less the fraction reflected back outside, used for photosynthesis if the building of interest is a greenhouse, and stored in the intrinsic thermal mass inside the building.

In common practice, Equation 5-10 is simplified for applications in barns and greenhouses.

8-6. System Characteristic Technique

8-6.1. The Technique. Sections 8-4 and 8-5 detail information to calculate ventilation when inlet geometry and the static pressure difference are known. However, the static pressure difference will not be known unless pressure/airflow characteristics of the fans used for ventilation are known. When that data is available, interactions between fans and inlets may be quantified. The method to relate fan and inlet characteristics is known as the "system characteristic technique".

Propeller fans are usually chosen to ventilate agricultural buildings. This type of fan provides the most efficient air moving capability at low static pressure differences. Data are generally available from fan manufacturers to characterize their fans. The general shape of a propeller fan curve is in Figure 8-10. The rate of air delivery is relatively constant when the pressure difference is small. The cutoff point depends on the fan, but is usually at least 100 Pa for fans typically used to ventilate barns and greenhouses.

Data for airflow through inlets has the general form shown in Figure 8-11. When the pressure difference is zero, airflow is zero. Airflow increases according to one of the slotted inlet equations already presented, or can be estimated for other inlets using the Bernoulli equation and a suitable coefficient of discharge.

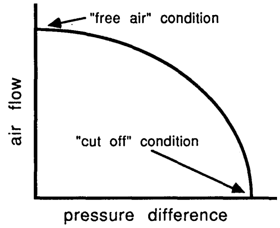


Figure 8-10. Representative curve showing how airflow provided by a (propeller) ventilating fan varies as a function of pressure difference across the fan.

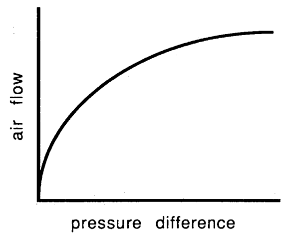


Figure 8-11. Representative curve showing how airflow rate through an inlet varies as a function of the pressure difference imposed across the inlet.

When fans draw air from an airspace and inlets provide fresh air, the airflow/pressure difference curves are as shown in Figure 8-12. When the inlet curve represents all inlets for the airspace and the fan curve represents all fans, the intersection of the two curves determines the operating (or balance) point of the inlet/fan system. The intersection must be the operating point, for it is the only point where the airflow and pressure difference are the same for both the fan and inlets and the two must be equal to satisfy airflow and air pressure continuity.

The system characteristic technique requires fan data be known for a candidate group of fans to be used for ventilation. Several possible inlet widths and the inlet type must be known. Application of the technique is best demonstrated using an example. Example 8-7 applies the design technique to a simple problem. It is a long example, but illustrates how a slotted inlet system might be designed.

Example 8-7

<u>Problem:</u> A barn is designed to house 250 dairy cows. Ventilation is to be an exhaust system, with inlets designed as shown as case (b) in Figure 8-8. A sketch of the barn is shown in Figure 8-13.

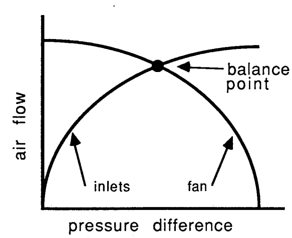


Figure 8-12. Representative curves of fans and inlets; the intersection point is where the combination of fans and inlets will operate in a steady flow state.

A compilation of fan data has been obtained:

Fan Model	Airflow Rate at the Listed Static Pressure Difference 0 Pa	10 Pa	20 Pa	30 Pa
A	1.28 m^3/s	1.22 m^3/s	1.13 m^3/s	0.99 m^3/s
B	2.19	2.08	1.93	1.80
C	2.72	2.58	2.39	1.93
D	3.04	2.89	2.68	2.41
E	4.01	3.81	3.53	2.96
F	4.52	4.29	3.98	3.68
G	5.19	4.93	4.57	4.22

Previous analysis has determined the required maximum ventilation rate to be 0.15 m^3/s per cow and the minimum rate to be 0.018 m^3/s per cow. Special care will be taken during construction to ensure air infiltration will be suppressed. As an assumption, the barn will be twice as tight as the "very tight" construction represented by Equation 8-31.

(a) Develop a graph to show the expected operation of the fans and slotted inlet system, at inlet widths of 0, 10, 20, 30, 40, and 50 mm. Use the pressure difference range of 0 to 30 Pa.

(b) Interpret any problems you may notice in the expected operation of the ventilation system.

Solution: As a first step the inlets will be analyzed, including infiltration (the unwanted inlets).

For slotted inlets with hinged baffles on the ceiling and airflow down the walls, Equation 8-26 applies,

$$\dot{V} = 0.0012W^{0.98}\Delta P^{0.49},$$

per meter of inlet. From the plan view of the barn in Figure 8-13, 170 m of the wall will be available on one side of the barn and 160 m on the other. Inlets will not be placed on end walls. However, the full 160 m on the wall with the milking center is not truly available. There are four fan banks on the wall and inlets directly over the fans would lead to some short-circuiting of fresh air.

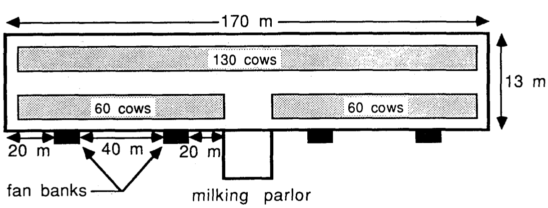


Figure 8-13. Plan view of dairy barn considered in Example 8-7.

Assume a 5 m section over each fan bank will have no inlets, thus, only 140 m of inlet can be on that wall, for a total of 310 m on both walls.

Total airflow through the slotted inlet system will be 310 times the flow per meter or

$$\dot{V}_{\text{slotted inlets}} = 0.372W^{0.98}\Delta P^{0.49}.$$

Infiltration will be at a rate half that indicated by Equation 8-31 or

$$\dot{V}/\text{cow} = 0.003\ \Delta P^{0.67}.$$

There will be space for 250 cows in the barn, so total infiltration will be

$$\dot{V}_{\text{infiltration}} = 0.75\ \Delta P^{0.67}.$$

When airflow through the slotted inlets and airflow from infiltration are added, the following describes all the inlets for the barn:

$$\dot{V} = 0.372W^{0.98}\Delta P^{0.49} + 0.75\Delta P^{0.67}.$$

To develop the system characteristic graph, total airflow as a function of static pressure difference must be calculated in the range from 0 to 30 Pa and for inlet widths of 0, 10, 20, 30, 40, and 50 mm. The equation above for total airflow yields data in the following table.

Static Pressure Difference	Airflow Rate, m^3/s, for Inlet Width, mm, as Shown					
	0	10	20	30	40	50
0 Pa	0.00	0.00	0.00	0.00	0.00	0.00
1	0.75	4.30	7.76	11.18	14.57	17.95
2.5	1.39	6.95	12.36	17.72	23.04	28.33
5	2.20	10.02	17.62	25.15	32.62	40.05
7.5	2.89	12.43	21.70	30.88	39.99	49.06
10	3.51	14.49	25.16	35.73	46.22	
15	4.60	17.99	31.02	43.90		
20	5.58	21.00	35.99	50.83		
25	6.48	23.68	40.41			
30	7.32	26.13	44.42			

Next accumulate airflow data for the fans. The maximum ventilation rate for the barn will be

$$\dot{V}_{max} = (0.15\ m^3/\text{s-cow})(250\ \text{cows}) = 37.5\ m^3/s.$$

The minimum rate will be

$$\dot{V}_{min} = (0.018\ m^3/\text{s-cow})(250\ \text{cows}) = 4.5\ m^3/s.$$

Table 6-1 contains data to be used as a guide for selecting stages between maximum and minimum ventilation rates. This barn is large, so for now assume a five-stage ventilation system will be used. In a real design, four, five, and six stages could be examined in detail and the best chosen.

With a five-stage system, 10%, 14%, 19%, 35%, and 100% are the idealized stages, but with the data for this example, the minimum stage is 12% of the maximum, not 10%. The staging schedule must be modified and one candidate is: 12%, 17%, 22%, 40%, and 100%.

Fans will be selected to provide this staging, approximately. The five stages are:

Stage	m^3/s
1	4.50
2	6.38
3	8.25
4	15.00
5	37.50

The fan data can be used to obtain a candidate set of fans to install in each bank. The static pressure difference during operation is not yet known, but likely will not be 0 Pa. Neither is it likely to be 30 Pa. For now assume the difference will be approximately 10 Pa and select fans accordingly. One additional criterion in selecting fans will be to make the four fan banks as similar as possible so air distribution will be as uniform as possible.

The following is presented as only one of many possible fan schedules. Symmetry in fan distribution among fan banks is a goal, but stage 4 violates that symmetry somewhat to achieve sufficient ventilation for the stage. A wider selection of fans would make the choice perhaps easier, but the selection which is shown was chosen to illustrate some of the difficulties in finding fan stages which closely match desired ventilation stages.

Stage	Total Air Fow	Fan Bank Number 1	2	3	4
1	4.88 m^3/s	A	A	A	A
2	6.60	B	A	A	B
3	8.32	B	B	B	B
4	15.28	A,B	A,B,B	A,B	A,B
5	38.68	A,B,B,F	A,B,B,F	A,B,B,F	A,B,B,F

In the table, letters refer to the fan or fans to operate in each bank in each stage. Each fan bank contains 4 fans, 1 of model A, 2 of model B, and 1 of model F. Control would be implemented so only the fans shown for each bank would operate at the appropriate stages. Control could be by thermostats, or by a computer.

After the fans have been selected, total airflow at each stage and at 0, 10, 20, and 30 Pa can be determined from fan data.

	Airflow Rate, m^3/s, at Static Pressure Differences of			
Stage	0 Pa	10 Pa	20 Pa	30 Pa
1	5.12	4.88	4.52	3.96
2	6.94	6.60	6.12	5.58
3	8.76	8.32	7.72	7.20
4	16.07	15.28	14.17	12.96
5	40.72	38.68	35.88	33.08

As an example calculation, for stage 2 at 20 Pa there will be 2 of model A and 2 of model B operating. At 20 Pa, fan model A delivers 1.13 m^3/s and fan model B delivers 1.93 m^3/s. Two of each provide a total of $2(1.13\ m^3/s + 1.93\ m^3/s) = 6.12\ m^3/s$.

The next step is to graph inlet airflow data and fan data on the same axes. Figure 8-14 shows the results. Recall that any intersection of a fan stage curve and an inlet airflow curve is a possible point of operation of the total system. Some would obviously be better than others.

A system characteristic graph such as in Figure 8-14 would not be used for control. Rather, it provides insight into operation of the ventilation system and can be used by a designer to avoid designing a problem ventilation system – one which never seems to work quite right.

One potential problem area when ventilation systems are designed for cold climates is the minimum ventilation stage. The required minimum ventilation rate for this example is 4.5 m^3/s. On Figure 8-14, stage 1 of the fans provides approximately 4.5 m^3/s when the inlet width is 0 mm and approximately 5 m^3/s when the inlet width is 10 mm. However, the pressure difference when the inlets are open 10 mm will be less than 2 Pa, a pressure with no capability to resist wind effects. A pressure difference of at least 10 Pa is preferred.

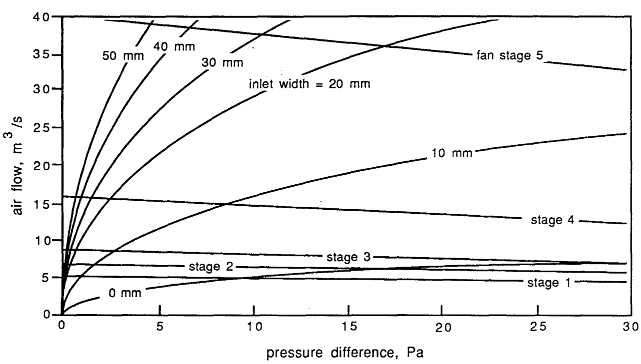


Figure 8-14. System characteristic graph for the dairy barn considered in Example 8-7.

The problem arises due to infiltration effects – infiltration provides all the ventilation needed for the minimum ventilation rate, but there is no guarantee fresh air distribution will be uniform. Likely it will not be. The problem of having low ventilation stages dominated by infiltration is common and indicates the importance of designing buildings to limit infiltration and specifying construction practices to seal all potential points of air infiltration. Also, research is needed to characterize current building designs and construction with regard to their infiltration characteristics.

If the design of the barn in this example were to be continued, an inlet width intermediate between 0 and 10 mm should be considered for adequacy. Practical construction considerations limit the minimum inlet width to no less than 5 mm (it is difficult to build a long inlet which can maintain only a slight opening). If 5 mm were adequate, extra precautions to limit infiltration would not be needed. However, it is likely the 5 mm inlet curve would intersect stage 1 ventilation at a pressure difference significantly less than 10 Pa. It would be a useful exercise to develop the data for an inlet 5 mm wide and add it to Figure 8-14.

The maximum required ventilation rate is 37.5 m^3/s, which can be obtained using an inlet width of only 30 mm. The operating static pressure difference at 30 mm will be approximately 10 Pa. If a greater pressure difference is desired to assure more vigorous air mixing and greater animal comfort during hot weather, a slightly narrower inlet and a different selection of fans could be found to provide such conditions.

A useful design factor which arises from knowing the maximum inlet width is knowledge of the minimum width of restriction upstream of the inlet. In this example, if 30 mm is chosen as the maximum inlet width and the factor of 2.5 times the maximum inlet width is used (as previously discussed), the building design should be specified so no section upstream of the slotted inlet would have a width narrower than 75 mm.

APPENDIX 3-1
SELECTED VALUES OF THERMAL CONDUCTIVITY[a]

Material	Thermal Conductivity, W/mK
Metals	
Aluminum (alloy 1100)	221
Brass, red (85% Cu, 15% Zn)	150
Brass, yellow (65% Cu, 35% Zn)	120
Copper (electrolytic)	393
Gold	297
Iron, cast	47.7 (327 K)
Iron, wrought	60.4
Lead	34.8
Nickel	59.5
Silver	424
Steel, mild	45.3
Tin	64.9
Zinc, galvanizing	110
Wood	
Ash, white	0.172
Elm, American	0.153
Fir, white	0.12
Mahogony	0.13
Maple, sugar	0.187
Oak, white	0.176
Pine, white	0.11
Spruce	0.11
Other	
Brick, building	0.7
Cardboard	0.07
Cellulose	.057
Charcoal, wood	0.05 (473 K)
Concrete stone	0.93
Cork granulated	0.048 (268 K)
Cotton, fiber	0.042
Earth, dry and packed	0.064
Glass, soda-lime	1.0 (366 K)
Ice, 0 C	2.24
Leather	0.16
Marble	2.6
Paper	0.13
Plaster	0.74 (348 K)
Sand, dry	0.33
Sawdust	0.05
Snow, fresh at 32 C	0.598

Selected from the 1985 ASHRAE Handbook of Fundamentals.

a. values at room temperature unless noted in parentheses.

APPENDIX 4-2
OVERALL THERMAL RESISTANCES OF GLAZINGS

A. Windows (vertical), no indoor shades, no storm sash

Type	Thermal Resistance, m^2K/W Winter	Summer
Single glass, clear,		
surface emittance of 0.84	0.16	0.17
0.60	0.17	0.18
0.40	0.19	0.20
0.20	0.22	0.23
Insulating glass, double,		
5 mm air space, 3 mm glass	0.29	0.27
6 mm air space, 3 mm glass	0.30	0.29
13 mm air space, 6 mm glass	0.36	0.31
Insulating glass, triple,		
6 mm air space, 3 mm glass	0.45	0.40

B. Windows (vertical), no indoor shades, glass outdoor storm sash with 25 mm air space

Type	Thermal Resistance, m^2K/W Winter	Summer
Single glass, clear,		
surface emittance of 0.84	0.43	0.36
0.60	0.37	0.29
0.40	0.40	0.29
0.20	0.43	0.36
Insulating glass, double,		
5 mm air space, 3 mm glass	0.48	0.43
6 mm air space, 3 mm glass	0.50	0.45
13 mm air space, 6 mm glass	0.56	0.45
Insulating glass, triple,		
6 mm air space, 3 mm glass	0.67	0.56

C. Adjustment factors for windows (multiply R-values in parts A and B by these factors)

	Wood Frame	Metal Frame
Single glass	1.05 - 1.18	0.91 - 1.00
Double glass	1.00 - 1.11	0.77 - 0.83
Triple glass	1.00 - 1.05	0.67 - 0.77
Storm sash applied over single glass	1.00 - 1.11	0.71 - 0.83
Storm sash applied over double or triple glass	1.00 - 1.05	0.67 - 0.77

D. Greenhouse Glazings

Material (includes surface resistance)	Unit Area Thermal Resistance, m^2K/W
Glass, single	0.16
Glass, double, 6 mm air space	0.25
Polyethylene film, single	0.14
Polyethylene film, double, 100 mm space	0.25
Fiberglass reinforced panel	0.15
Double panel, acrylic or polycarbonate	0.35

Notes:

a. Winter conditions are -18 C outdoor air, 21 C indoor air, and 24 km/hr (6.67 m/s) wind speed.
b. Summer conditions are 32 C outdoor air, 24 C indoor air, solar radiation of 782 W/m^2, and 12 km/hr (3.33 m/s) wind speed.
c. Manufacturer's data should be consulted for more accurate data for specific products, especially for thermally improved windows.
d. Data obtained from the ASHRAE Handbook of Fundamentals. Consult that reference for more detail and other glazing configurations.

APPENDIX 4-3
OVERALL THERMAL RESISTANCES OF DOORS

A. Wood doors, no storm doors

Type	Thermal Resistance, m²K/W Winter	Summer
Flush doors		
hollow core, 35 mm thick	0.37	0.39
hollow core, 44 mm thick	0.38	0.40
with single glazing	0.28	0.33
solid core, 35 mm thick	0.45	0.46
solid core, 44 mm thick	0.53	0.55
with single glazing	0.38	0.40
with double glazing	0.48	0.49
solid core, 57 mm thick	0.65	0.68
with single glazing	0.43	0.44
with double glazing	0.53	0.55
Panel doors		
11 mm panels, 35 mm thick door	0.31	0.33
11 mm panels, 44 mm thick door	0.33	0.34
with single glazing	0.26	0.28
with double glazing	0.35	0.37
29 mm panels, 44 mm thick door	0.45	0.46
with single glazing	0.29	0.30
with double glazing	0.40	0.42

B. Wood doors, with storm doors, winter conditions only

Type	Thermal Resistance, m²K/W wood storm door	metal storm door
Flush doors		
hollow core, 35 mm thick	0.59	0.55
hollow core, 44 mm thick	0.61	0.55
with single glazing	0.53	0.49
solid core, 35 mm thick	0.68	0.63
solid core, 44 mm thick		
with single glazing	0.61	0.55
with double glazing	0.70	0.65
solid core, 57 mm thick	0.88	0.84
with single glazing	0.65	0.61
with double glazing	0.76	0.70
Panel doors		
11 mm panels, 35 mm thick door	0.53	0.48
11 mm panels, 44 mm thick door	0.55	0.49
with single glazing	0.49	0.43
with double glazing	0.57	0.52
29 mm panels, 44 mm thick door	0.68	0.63
with single glazing	0.52	0.46
with double glazing	0.63	0.57

C. Steel doors

Type	Thermal Resistance, m^2K/W Winter	Summer
Solid urethane foam core, no thermal break, 44 mm thick, no storm door	0.44	0.45
Solid urethane foam core, with thermal break, 44 mm thick,		
no storm door	0.93	0.98
wood storm door	1.10	
metal storm door	1.03	

Notes:

a. Data is based on nominal door size of 1.12 m by 2.03 m.
b. Winter conditions are -17.8 C outdoor air temperature, 21.1 C indoor air temperature, and 24 km/hr (6.67 m/s) wind speed.
c. Summer conditions are 31.7 C outdoor air temperature, 23.9 C indoor air temperature, and 12 km/hr (3.33 m/s) wind speed.
d. Wood storm door values are for 50% glass area; metal storm door values are for any glass area.
e. Flush door values are for 17% glass area; double glazing with 6.35 mm air space.
f. Panel door values are for 55% panel area; glazed panel door values are for 33% glass area and 22% panel area; double glazing with 6.35 mm air space.
g. Data obtained from the ASHRAE Handbook of Fundamentals.