INFLUENCE OF MANURE-HANDLING SYSTEMS ON HEAT AND MOISTURE LOADS IN FREE-STALL DAIRY HOUSING

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Six commercial free-stall dairy barns, three with scraped and three with slatted passageways, were monitored over a continuous 48-h period to determine the influence of these two manure-handling systems on heat and moisture loads within such units. Mean measured total heat loads compared favorably with existing design data. The barns with solid passageways produced more latent heat than the barns with slatted passageways, the mean measured latent heat loads being 1758 and 1600 kJ/(h·cow (500 kg)), respectively. Design latent heat data, at corresponding temperatures, was exceeded in all cases. Animal sensible heat converted to latent heat within the barns with solid and slatted passageways was estimated to be 28.7 and 25.0%, respectively. The ratio of latent to total heat in the exhaust air ranged from 0.34 to 0.47, the average for the six barns being almost 0.40. Ambient temperature appeared to affect heat loads more than did the floor type.

INTRODUCTION

Reliable animal heat and moisture production data are necessary for the design of functional environmental control systems. In the case of dairy cows, data on heat and moisture production are available from various sources including the Canadian Farm Building Code (Associate Committee on the National Building Code 1977), American Society of Agricultural Engineers Yearbook of Standards (1983) and the Midwest Plan Service (1983). These data, however, are based very largely on studies by Yeck and Stewart (1959) under conditions which were very different from today's commercial operations. Turnbull (1973) reasoned that the moisture loads in free-stall barns, due to the large wet surface of passageways, probably would be greater than those in tie-stall units where conditions are somewhat similar to the facilities used by Yeck and Stewart (1959). This was confirmed by Smith et al. (1980) who found moisture loads to be significantly higher in two free-stall barns with scraped passageways than in two tie-stall operations.

Free-stall dairy units, however, utilize two different manure-handling systems, one involving solid concrete passageways which are scraped regularly, and the other slatted passageways with pits beneath in which manure is stored for several months. The effect of these manure-handling systems on heat and moisture loads in free-stall units is unknown. Accordingly, a study was initiated, the results of which are reported here, to determine the effects on these loads of the two manure-handling systems in free-stall barns under commercial conditions.

EXPERIMENTAL FACILITIES

Six free-stall barns, three with solid and three with slatted passageways, were chosen from among 25 commercial, free-stall operations examined in the Edmonton area of Alberta. These barns were selected for monitoring on the basis of farmer cooperation, accessibility, and the feasibility of instrumenting the structure. Each unit was representative of the majority of free-stall dairy barns in Alberta. The study commenced in mid-November, 1983 and was completed by April, 1984. There was no disruption to the normal operation of any of the barns during the monitoring period.

Four barns were of insulated wood-frame construction, one of wood-frame and cinder block, while the sixth was constructed from concrete block. This latter barn was also the only barn without translucent plastic sections running along the sidewalls. The six barns had insulated false ceilings, and negative pressure, mechanical ventilation systems. Typically, each barn had two rows of stalls along the outer walls and a central feed alley. The larger barns had extra stalls located at one end of the feedbunk. Twice-daily milking at approximately 12-h intervals was practiced in all six operations. The cows in the six units were all Holsteins and were estimated by their respective owners to average 550 kg liveweight. Since one barn housed several cattle other than cows, their estimated weights were totalled and then expressed on a cow-equivalent basis for the purpose of this study. In the three barns with solid passageways, the manure was scraped mechanically to a cross-conveyor or sump and removed from the bulding on a daily basis. The three barns with slatted passageways utilized slats with a nominal top width and spacing of 5.5 and 1.75 inches, respectively. Some of the pertinent management and housing features of the six barns are described briefly as follows while Table I summarizes their operational characteristics.

TABLE I. OPERATIONAL CHARACTERISTICS, MEAN VALUES

Passageways	Barn		
Solid	SO-1	SO-2	SO-3
Number of 550-kg cow equivalents	60	37	42
% cows milking	97	85	86
Milk production (kg/(cow·day))	24.5	20.0	18.9
Water consumption (kg/(cow·day))	80.0	87.2	71.1
Stocking density (m^2/cow)	10.5	12.7	9.6
Stocking rate (% of barn capacity)	86	76	81
Solid alleys (% of barn area)	54	54	49
Exposure factor (kJ/(h·°C·cow))	32.0	25.0	29.7
Slatted	SL-1	SL-2	SL-3
Number of 550-kg cow equivalents	154	61	150
% cows milking	96	95	100
Milk production (kg/(cow·day))	24.9	16.0	22.3
Water consumption (kg/(cow·day))	69.6	50.2	74.2
Stocking density (m^2/cow)	4.8	9.1	5.6
Stocking rate (% of barn capacity)	100	81	100
Slatted alleys (% of barn area)	46	54	48
Exposure factor (kJ/(h·°C·cow))	13.4	33.3	9.6

Barn SO-1 — Solid Passageways

This was a conventionally designed structure, measuring 14 × 47 m, with straw-filled earthen-floored stalls. The central feedbunk was filled by a conveyor; the cows were fed alfalfa haylage and a grain ration in the parlor. Ventilation was provided by three evenly spaced, thermostatically controlled, 610-mm-diameter fans, located 1.17 m down the 2.9-m-high wall. One fan was two-speed; the others were constant speed units. Fresh air entered through a discontinuous, adjustable slot inlet along the opposite wall.

Barn SO-2 — Solid Passageways

This barn also had straw-filled earthen-floored stalls and measured 13 × 36 m. The cows were fed in a central feedbunk, the hay being brought into the barn twice daily by tractor. A protein supplement was provided daily in the milking parlor. Three evenly spaced, thermostatically controlled constant-speed 400-mm-diameter fans were located 0.35 m down the 2.6-m-high wall. Fresh air was provided by an adjustable inlet in the center of the ceiling.

Barn SO-3 — Solid Passageways

As in Barn SO-2, the cows in this unit were fed baled hay from the drive-through central feedbunk that was used both for storage and feeding. The animals also received a grain ration in the parlor. The barn area was 14 × 33 m. Straw was used liberally for bedding on the earthen-floored stalls. Two 610-mm-diameter fans, one two-speed, the other single-speed, provided ventilation, with fresh air entering through discontinuous non-adjustable slot inlets on the opposite wall. The fans were mounted side by side 1.1 m down the 2.9-m-high wall.

Barn SL-1 — Slatted Passagewas

This large building, which had been constructed in two stages, measured 12 × 56 m. A belt conveyor transported an alfalfa/high-moisture barley feed along the central feedbunk. Sawdust was spread weekly on the concrete-floored stalls. Ventilation was provided by four continuously running 400-mm-diameter constant-speed fans on one wall, with discontinuous nonadjustable slot openings on the opposite wall providing the fresh air. In the older part of the barn, two fans were located 0.61 m down a 2.34-m-high cinder-block wall. The other two fans were located 0.61 m down a 2.74-m-high wood-frame wall. The manure pit was cleaned out approximately 2 mo prior to monitoring. Wash water was added intermittently to the pit.

Barn SL-2 — Slatted Passageways

This barn was the only concrete-block structure and measured 13 × 40 m. Barley/oat haylage was brought to a center feedbunk by conveyor. Ventilation was provided by two 300-mm-diameter and one 500-mm-diameter manually controlled constant-speed fans, located 0.6 m down the 2.5-m-high wall. Fresh air entered through fixed openings in windows in the sidewalls. The manure pit was almost empty during the monitoring period, prior to which the cows were outside.

Barn SL-3 — Slatted Passageways

This unit, similar to Barn SL-1, was large, having an area of 13 × 70 m. A conveyor belt along the central feedbunk carried the alfalfa haylage and rolled oats to the animals. Ventilation was provided by two thermostatically controlled constant speed 700-mm-diameter fans located directly opposite each other about one-third the way along the length of the barn. They were mounted 1.0 m down the 2.7-m-high walls. Two heat exchangers (Del Air, Model A-800) were located near the ends of one wall, 1.9 m off the ground. In addition to recovering heat, these assisted in barn ventilation. Fresh air entered through discontinuous slot inlets on both sidewalls. Hot-water pipes underneath the earthen-floored stalls, for approximately three-quarters of the way around the barn, maintained dry and comfortable lying conditions. Five 900-mm-diameter ceiling fans were spaced evenly and longitudinally along the center of the barn to assist in air circulation. This barn contained eight calves and two bulls in addition to the lactating cows. The manure pit was about to be emptied at the time of monitoring.

EXPERIMENTAL PROCEDURES AND INSTRUMENTATION

To perform a simultaneous heat and moisture balance on a free-stall dairy barn, the data acquisition system developed by Feddes and McQuitty (1977) was employed to monitor continuously the thermal environment over a continuous 48-h period.

Barn ventilation rates were determined by constructing insulated discharge ducts, incorporating air-straighteners, downstream of each exhaust fan. A thermistor anemometer (Airflow Developments, Buckinghamshire, U.K.) was used to measure the air-flow rates over a 25-point duct profile, three to four times daily during the monitoring period, and more frequently during rapidly changing climatic conditions. A hot-wire anemometer (Kurz Instruments, Carmel Valley, Calif.) was used to check these readings. Hall-effect sensors were mounted on the shafts of those fans that were either variable or two-speed in operation. By calibrating air flow against fan speed over the entire range of a fan, a functional relationship was developed between the two parameters. In the case of constant-speed fans, a thermistor (Fenwal Electronics, Framingham, Mass.) was placed in the fan ducting to determine the fan on/off state.

The energy contents of the inlet and exhaust air, including the air passing through the heat exchangers in Barn SL-3, were calculated from the respective dry-bulb temperatures and dewpoints. Thermistors were placed at the top and bottom of each fan, and one each in the attic and outside. In addition, each barn was divided into eight sections, quarters by length and halves by width, and a thermistor located, either 400 mm below the ceiling or at animal level, at the center of each section to measure the actual ambient temperature throughout the barn as opposed to exhaust conditions. Dewpoints were recorded by sampling outside, inside and exhaust air through a dewpoint hygrometer (Model 880, Cambridge Systems, Mass.). A check on the measured dewpoints was provided by recording wet-bulb temperatures in the center of each barn using a thermistor-based wet-bulb sensor. Hand-held psychrometers also were used regularly to measure the instantaneous dry-bulb and wet-bulb temperatures, thus checking the sensor outputs.

Conductive heat losses were measured using heat-flux plates (DeShazer et al. 1982). These were placed on a representative section, as determined by an infrared pyrometer (Omega Engineering, Stamford, Conn.), of each structural component of a barn, i.e., walls, floor, and ceiling. These measured values were checked against those calculated from the known thermal resistances and areas of the building components (exposure factor, Table I), and the temperature difference across the components.

In Barn SL-3, supplemental heat output from the imbedded water pipes was determined by placing thermistors on the inlet and outlet pipes at the barn entry and exit points, and by measuring the water-flow rate with an ultrasonic Doppler flowmeter (Polysonics Flowmeter, Houston, Tx.). The proportion of heat flowing upwards through the earthen floor was measured using a commercially available heat-flow meter (Concept Engineering, Old Saybrook, Conn.) and was found to be 0.7 times the total heat generated

TABLE II. SUMMARY OF THE PRIMARY SENSORS, THEIR LOCATIONS AND SCANNING RATE, FOR A TYPICAL BARN MONITORED

Sensor type and sampling rate	Location	Number of sensors
Thermistors (20-min)	Attic	1
	Outside	1
	400 mm below ceiling level	5
	Cow level	3
	Wet-bulb	1
Thermistors (4-min)	At each fan (high and low)	2 per fan
	Downstream of fan	1 per duct
Heat-flux plates (20-min)	Ceiling	1
	Walls	4
	Floor	1
Sequential dewpoint sampling (30-min)	Exhaust	1 per fan
	Ambient	3
	Outside	1
Static pressure differential (4-min)	Center of barn	1
RPM sensor (4-min)	Variable or 2-speed fans	1 per fan
Water consumption (daily)	Trough water line	1
Wet-bulb meter (4-min)	Center of barn	1

TABLE III. SUMMARY OF ENVIRONMENTAL PARAMETERS FOR THREE SOLID PASSAGEWAY BARNS (MEAN VALUES)

	Barn		
Parameter	SO-1	SO-2	SO-3
Ventilation rate (L/(s·cow))	41.7	48.5	75.9
Range	(23/64)	(22/73)	(58/76)
Outside temperature (°C)	−10.0	−8.7	5.8
Range	(−5/−18)	(6/−19)	(16/−1)
Exhaust temperature (°C)	4.3	7.4	13.6
Range	(3/6)	(5/14)	(10/19)
Animal level temperature (°C)	4.0	8.2	13.6
Range	(2/6)	(7/13)	(10/19)
Ceiling temperature (°C)	5.5	8.9	14.0
Range	(5/7)	(8/14)	(10/19)
Inside relative humidity (%)	88	84	71
Range	(82/100)	(64/95)	(44/84)
Static pressure differential (mm WG)	4.20	0.64	0.77
Range	(2.0/5.0)	(0.5/0.8)	(0.6/0.8)

TABLE IV. SUMMARY OF ENVIRONMENTAL PARAMETERS FOR THREE SLATTED PASSAGEWAY BARNS (MEAN VALUES)

	Barn		
Parameter	SL-1	SL-2	SL-3
Ventilatation rate (L/(s·cow))	40.6	49.1	28.5
Range	(38/44)	(46/69)	(28/29)
Outside temperature (°C)	−1.7	−5.1	−4.2
Range	(3/−7)	(1/−10)	(4/−12)
Exhaust temperature (°C)	12.9	7.2	15.5
Range	(11/15)	(5/9)	(12/18)
Animal level temperature (°C)	11.9	7.2	13.0
Range	(10/13)	(5/10)	(9/17)
Ceiling temperature (°C)	13.5	7.4	13.8
Range	(12/16)	(6/9)	(9/18)
Inside relative humidity (%)	73	82	70
Range	(65/83)	(79/90)	(64/80)
Static pressure differential (mm WG)	0.51	0.40	1.02
Range	(0.3/1.0)	(0.3/0.8)	(0.8/1.3)

within the pipes. One additional minor source of supplemental heat, lighting, was measured in all barns and used in the determination of total heat loads in the barns.

Several other parameters that related indirectly to the barn heat and moisture production and helped explain or verify trends and information in the data were measured. These included static pressure differential between the inside and outside of each barn using a low-range pressure differential transducer (Validyne, Model DP45, Sierra Instruments, Calif.), and water consumption by the animals using a water meter (Neptune Meters, Toronto, Ont.) placed in the water-trough feed line. Table II summarizes the primary sensors, their location and scanning rate.

DATA PROCESSING AND ANALYSIS

The output signals from each instrument were received and processed by a data logger (Feddes and McQuitty 1977) and finally recorded on paper tape or, if necessary, on a portable terminal and three-pen chart recorder. The paper tape data were transformed into raw voltage data by a tape-reader at the Computing Services Centre, University of Alberta, Edmonton, Alta. Utilizing a computer program, the data then were processed into their real values and averaged over each hour. Finally, using standard psychrometric equations (American Society of Heating, Refrigeration and Air-Conditioning Engineers 1981), properties of the incoming and exhaust air and ventilation rates were calculated.

Sensible and latent heat changes in the air as it passed through the barn were determined. Adding the conductive and ventilation heat losses and subtracting the supplemental heat gains yielded the animal total heat output together with the latent heat arising from the animals and by evaporation of moisture from wet surfaces within the building. Animal sensible heat output was represented by the difference between these total and latent heat data. A further discussion of the energy balance within confinement housing may be found in the Midwest Plan Service Handbook (1983).

RESULTS AND DISCUSSION

Tables III and IV list some of the pertinent environmental parameters monitored for the solid and slatted barns, respectively. The variation in outside temperature, from an average temperature of −10°C for the first barn monitored, SO-1, to an average of 5.8°C for the last barn monitored, SO-3, influenced the ventilation rates required for temperature and moisture control in all the barns and, consequently, the heat and moisture production in the barns. However, the ventilation system response in each barn can be gauged by the range of inside temperature compared to the outside temperature. For example, from Table III, the outside temperature for Barn SO-1 varied from −5 to −18°C while the inside temperature remained relatively constant, ranging from 3 to 6°C at the fan outlets.

Somewhat surprisingly, the vertical temperature gradients were only 1.6°C or less despite, with one exception (Barn SO-1), static pressure differentials being maintained at very low levels compared to a minimum recommended value of 1.3 mm (Munroe et al. 1982). Barn rela-

TABLE V. MEAN BUILDING HEAT BALANCE COMPONENTS

Passageways	Barn			Mean values
Solid	SO-1	SO-2	SO-3	
Total barn heat production (kJ/(h·cow (500 kg)))	4122	4489	4561	4391
Conductive heat loss (kJ/(h·cow (500 kg)))	417	366	209	331
Ventilation heat loss (kJ/(h·cow (500 kg)))	3705	4132	4352	4060
Supplemental heat (kJ/(h·cow (500 kg)))	32	31	31	
Conductive/total	0.10	0.08	0.05	0.08
Slatted	SL-1	SL-2	SL-3	
Total barn heat production (kJ/(h·cow (500 kg)))	4250	4251	3377	3959
Conductive heat loss (kJ/(h·cow (500 kg)))	177	371	170	239
Ventilation heat loss (kJ/(h·cow (500 kg)))	4073	3880	3207	3720
Supplement heat (kJ/(h·cow (500 kg)))	6	76	36	
Conductive/total	0.04	0.09	0.05	0.06

TABLE VI. MEASURED TOTAL, SENSIBLE AND LATENT HEAT PRODUCTION (kJ/(h·cow (500 kg)))

Passageways	Barn			Mean values
Solid	SO-1	SO-2	SO-3	
Temperature (°C)	4.3	7.4	13.6	8.4
Total heat production	4090	4458	4530	4360
Sensible heat production	2709	2686	2409	2602
Latent heat production	1381	1772	2121	1758
Latent heat/ total heat	0.34	0.40	0.47	0.40
Slatted	SL-1	SL-2	SL-3	
Temperature (°C)	12.9	7.2	15.5	11.8
Total heat production	4244	4175	3341	3920
Sensible heat production	2444	2574	1943	2320
Latent heat production	1800	1601	1398	1600
Latent heat/ total heat	0.42	0.38	0.42	0.41

tive humidities tended to be higher than normally considered desirable, particularly in the units with solid passageways. They also reflected the tendency of all the operators to ventilate on the basis of temperature control, even in those units where thermostats were not used. Thus, relative humidities tended to reflect outside temperatures in that values were higher during colder weather. The use of heat exchangers in Barn SL-3 appeared to contribute favorably to the ambient conditions recorded within it.

Mean building heat balance components for the six barns monitored are given in Table V and are expressed for convenience in terms of kilojoules per hour per cow of 500 kg liveweight. In a heat balance for an animal confinement building, the major component of heat losses normally is that due to ventilation. This varied from 90% of the total heat loss in Barn SO-1 to 96% in Barn SL-1 (Table V).

Subtracting the supplemental heat figures from the total barn heat production of Table V gives rise to the mean measured animal total, latent and sensible heat production presented in Table VI. While all six barns were not maintained at the same temperature during the period in which each was monitored, the results were reasonably consistent, particularly with respect to total heat production. Barn temperatures were considered to be within the zone of thermoneutrality for lactating cows and, consequently, variation in total heat production could not be explained in terms of temperature alone. Other probable, contributing factors included level of milk production, feed energy intake, stocking density and its influence on animal activity, and management differences between herds.

In general, the latent heat removed by ventilation (Table VI) from the barns with solid passageways was higher than that removed from barns with slatted passageways by almost 10%. However, the latent heat loads in the three warmest barns (Tables III and IV) were, on average, higher by nearly 12% than those in the three cooler barns. Thus, the temperature at which a free-stall dairy barn is operated in practice would seem to have an influence on moisture loads comparable to the manure-handling system. The quantity and quality of bedding used, and the type of manure, also may have had a minor influence on moisture loads. In all six barns the passageways were predominantly wet regardless of management or physical parameters.

The measured animal heat productions were compared (Table VII) with those calculated from equations derived by Yeck and Stewart (1959) and Strom and Feenstra (1980). The equations of the former authors were based on data more appropriate to a tie-stall dairy facility so that a direct comparison may seem inappropriate. However, as noted earlier, their data are used widely for design purposes. Strom and Feenstra (1980) on the other hand, in an extensive review of the literature, considered not only barn temprature in their predictions of total and latent heat outputs for dairy cows but also milk production levels and stage of pregnancy.

Total heat values predicted by Yeck and Stewart (1959), from Table VII, were on average 3.5% lower than the values measured in this study. Smith et al. (1980) also found that total heat production was slightly lower in tie-stall than in free-stall units. The difference in activity level of cows maintained under the two systems would appear to be a logical explanation for this increase in total heat production in the free-stall operations. Of interest is the fact that the Strom and Feenstra (1980) predicted total heat values for cows were also lower than the measured values, the average being 3.4% lower.

The difference between the measured and predicted latent heat values (Table VII) are striking in that the former far exceeded the maximum predicted by the previous research. On average, the measured values were 27.6 and 68.8% higher than the Yeck and Stewart and the Strom and Feenstra predictions, respectively. The differences between measured and predicted values were more pronounced for the barns with solid passageways than for those utilizing slats, this being a reflection of the higher moisture loads associated with the former system.

The measured latent heat to total heat ratios for the three barns with solid passageways averaged 0.40, while the ratios for the slatted units averaged 0.41 (Table VI). The similarity of these results would suggest that the ratio of latent to total heat removed by ventilation is more a characteristic of free-stall housing than of the manure-handling system used within them. The average ratios for the three coolest and three warmest barns were 0.37 and 0.44, respectively. This again emphasizes the significance of barn temperature on moisture loads, the higher the temperature the greater the evaporation taking place from wet surfaces.

The moisture removed by ventilation as latent heat in the six barns studied included that produced by the animals and that due to evaporation from wet surfaces within the building. This latter component of the moisture load involves a conversion of animal sensible heat to latent heat. This

TABLE VII. COMPARISON OF MEAN MEASURED HEAT PRODUCTION WITH DESIGN DATA (kJ/(h·cow (500 kg)))

Passageway	Barn			Mean values
Solid	SO-1	SO-2	SO-3	
Total heat production				
Measured	4090	4458	4530	4360
Predicted				
Yeck and Stewart (1959)	4182	4085	3890	4050
Strom and Feenstra (1980)	4330	3897	3788	4005
Sensible heat production				
Measured	2709	2686	2409	2602
Predicted				
Yeck and Stewart (1959)	3022	2845	2489	2785
Strom and Feenstra (1980)	3400	3006	2765	3057
Latent heat production				
Measured	1381	1772	2121	1758
Predicted				
Yeck and Stewart (1959)	1165	1238	1408	1270
Strom and Feenstra (1980)	930	891	1023	948
Slatted	SL-1	SL-2	SL-3	
Total heat production				
Measured	4244	4175	3341	3920
Predicted				
Yeck and Stewart (1959)	3912	4091	3831	3945
Strom and Feenstra (1980)	4378	3504	4122	4001
Sensible heat production				
Measured	2444	2574	1943	2320
Predicted				
Yeck and Stewart (1959)	2529	2856	2380	2588
Strom and Feenstra (1980)	3252	2726	2906	2961
Latent heat production				
Measured	1800	1601	1398	1600
Predicted				
Yeck and Stewart (1959)	1384	1238	1457	1360
Strom and Feenstra (1980)	1126	778	1216	1040

TABLE VIII. CONVERSION OF SENSIBLE TO LATENT HEAT (kJ/(h·cow (500 kg)))

Passageways	Barn			Mean values
Solid	SO-1	SO-2	SO-3	
Animal latent heat production (Yeck and Stewart 1959)	614	664	851	710
Percentage of sensible heat converted	22	29	35	29
Building latent heat/total latent	0.56	0.63	0.60	0.60
Slatted	SL-1	SL-2	SL-3	
Animal latent heat production (Yeck and Stewart 1959)	807	656	955	806
Percentage of sensible heat converted	29	27	19	25
Building latent heat/total latent	0.55	0.59	0.32	0.49

TABLE IX. SUMMARY OF CORRELATION COEFFICIENTS† BETWEEN INSIDE TEMPERATURE AND HEAT PRODUCTION FOR SIX BARNS

Passageways	Barn		
Solid	SO-1	SO-2	SO-3
Total heat production	−0.25	−0.23	−0.26
Sensible heat production	−0.26	−0.40	−0.68
Latent heat production	−0.14	+0.12	+0.32
Slatted	SL-1	SL-2	SL-3
Total heat production	−0.22	−0.11	−0.72
Sensible heat production	−0.50	+0.12	−0.86
Latent heat production	+0.26	−0.49	+0.30

†Critical value of $r = \pm 0.285$ (Steel and Torrie 1980).
Significance level of 5%, 46 degrees of freedom.
−, denotes a negative correlation; +, denotes a positive correlation.

could explain the discrepancy between the measured and the predicted laten heat values of Strom and Feenstra (1980) who utilized physiological data in the derivation of their equations. The equations of Yeck and Stewart (1959) accounted for this evaporation but not in the context of free-stall housing.

In this study, the extent of this conversion of sensible to latent heat could not be calculated directly. Because of its significance in determining moisture loads in free-stall housing, however, an estimate was made of the extent to which this was occurring in the six barns monitored. Data from the work reported by Yeck and Stewart (1959) were used to calculate the theoretical latent heat output for the cows in each unit. The percentages of the animal sensible heat converted to latent then were determined (Table VIII). The average percentage values were 28.7 and 25.0 for the barns with solid and slatted passageways, respectively, the overall average for the six barns monitored being almost 27%. This conversion of animal sensible heat had a marked effect on the moisture loads to be removed by ventilation from these free-stall barns, the "building" latent heat on average accounting for 59.7 and 48.7% of the total heat in the units with solid and slatted passageways, respectively, the overall average for the six barns being 54.2%. These values were substantially greater than those indicated by Yeck and Stewart (1959) for their tie-stall facilities. These authors reported that, at temperatures up to 10°C, 40−45% of the moisture load was attributable to evaporation from wet surfaces, with the proportion of the total latent heat directly attributable to the animal increasing as temperatures rose above 10°C.

STATISTICAL ANALYSIS

While six barns was regarded as the minimum number necessary for this study, it also was the maximum number that could be monitored with available resources. This latter fact imposed limitations with regard to statistical analysis of the data. Since dairy barn operations may vary widely, assumptions were necessary to effect a valid comparison. In this regard, factors such as the genetic characteristics of the herds, the nutritional values of the feeds and the management practices of the operators were assumed to be similar among all six barns.

Linear Correlation

The principal environmental parameter influencing animal heat and moisture production is temperature. The SPSSX subprogram for bivariate correlation, SCATTERGRAM, was employed to measure the degree of correlation between animal heat production and the inside barn temperature. Table IX summarizes the coefficients of linear correlation for the six data sets.

The total heat production was not significantly dependent at the 5% level on barn temperature except in Barn SL-3. This result was expected, since the barn temperatures recorded were within the zone of thermoneutrality of cows where total heat production is considered to be constant. However, the negative correlation in all six barns suggests that as ambient temperature increases, the total heat production tends to decrease, contrary to what was anticipated.

The sensible heat production displayed a significant negative correlation in four barns with the ambient temperature. Of interest was the fact that there was a negative correlation between sensible heat production and barn temperature in all

TABLE X. SUMMARY OF STUDENT'S *t* VALUES† COMPARING THE DESIGN AND MEASURED HEAT PRODUCTION DATA FOR THE TWO FLOOR SYSTEMS

	Student's *t* value	
Passageways	Yeck and Stewart (1959)	Strom and Feenstra (1980)
Solid		
Total heat production	1.91 (−)‡	1.65 (−)
Sensible heat production	1.00 (−)	2.18 (++)
Latent heat production	2.16 (++)	3.73 (+)
Slatted		
Total heat production	0.08 (−)	0.21 (−)
Sensible heat production	1.12 (−)	2.60 (++)
Latent heat production	1.81 (−)	3.16 (+)

†Student's *t* test on the hypothesis that the mean values of the measured and design heat production data are equal.
‡ −, denotes failure to reject the hypothesis; +, rejection of hypothesis at 5% level of significance; ++, rejection of hypothesis at 10% level of significance.

TABLE XI. SUMMARY OF RESULTS FROM DUNCAN'S MULTIPLE RANGE TEST ON THE MEANS OF THE MEASURED DATA

Barn SO-1 = 1, SO-2 = 2, SO-3 = 3; Barn SL-1 = 4, SL-2 = 5, SL-3 = 6

	Duncan package						Standard error
Total heat production	6	1	5	4	2	3	137.02
			–	–	–	–	
		–	–	–	–		
	–						
Sensible heat production							
Solid passageways	3	2	1				115.06
		–	–				
	–	–					
Slatted passageways	6	4	5				73.18
		–	–				
	–						
Latent head production							
Solid passageways	1	2	3				87.47
			–				
		–					
	–						
Slatted passageways	6	5	4				36.56
			–				
		–					
	–						

cases except Barn SL-2. This result was in agreement with predicted trends. Latent heat production, however, displayed a poor correlation with the prevailing temperature, although, as was pointed out earlier, the latent heat loads in the three warmest barns were higher than in the three coolest.

The influence of ambient relative humidity on heat production was examined. However, this parameter had a much lesser effect on heat production than did temperature.

Statistical Comparison between Measured and Design Data

The Student *t* test criterion for hypothesis testing was performed on the measured and design animal heat production data. The hypothesis tested was that there was no difference between their respective total, sensible and latent heat mean values (Table X). The assumption was made that the population variances were equal.

When testing at the 5% level of significance, only the measured latent heat loads of both housing systems did not agree statistically with the design data of Strom and Feenstra (1980). Due to the small sample size of the experiment, further testing of the hypothesis at the 10% level was performed. In addition to the previous rejections, a significant difference was observed between the measured sensible heat loads and those predicted by Strom and Feenstra. The latent heat loads in the barns with solid passageways proved to be significantly different to those prescribed by Yeck and Stewart (1959).

Multiple Comparison of Measured Means

The multiple comparison procedure, Duncan's multiple range test, which is based on standard errors, was performed on the means of the measured total, sensible and latent heat data from each barn. The results are summarized in Table XI. All confidence testing was at the 5% level.

With respect to analysis of the statistical comparisons of Table XI, any two or more means underscored by the same line indicate no significant differences between those means. Among the more noteworthy results was the agreement between the total heat production means of five of the six barns, Barn SL-3 being the notable exception to this agreement. The means of the latent heat production in the separate analysis of the three solid and three slatted-floor barns displayed significant differences. The corresponding sensible heat production means displayed less variability. Such statistical conclusions may indicate the greater influence of the thermal environment on barn latent heat production than on sensible heat production.

Further Comparison of Heat Loads in Barns with Solid and Slatted Passageways

In this study, the average ambient temperature of the six barns ranged from 4.2 to 15.4°C. In analyzing the data for the two manure-handling systems, a comparison of heat loads adjusted for inside temperature variation would be more meaningful than comparison among unadjusted heat loads. This would exclude the observed variation in heat production of the six barns that may be attributable to the variation in inside temperature under which the data were collected. In an effort to remove this variation in the data due to temperature, a homogeneity of regression, modelled by Gujarti (1970), was utilized. The regression lines of total, sensible and latent heat loads for both manure-handling systems, based on a common dependent variable, namely temperature, were compared. At the 5% level of significance, there was no significant difference between the slopes of the three sets of regression lines. Tests at the 10% level yielded similar results. However, at the 20% level of significance, a significant difference occurred between the slopes of both latent heat regression equations. This result indicates that the greatest difference between slatted and solid floors lies between the latent heat production of the two manure-handling systems.

CONCLUSION

Based on the results of this study, the following conclusions were drawn.

(1) Total heat output in the free-stall dairy barns was on average 3.5% higher than the design values reported in the literature, and varied from 3341 to 4458 kJ/h·cow (500 kg)).

(2) Latent heat loads exceeded design values by an average of 27.6%, and ranged from 1381 to 2121 kJ/(h·cow (500 kg)).

(3) The average moisture loads in the units with solid passageways exceeded those with slatted passageways by 10%, the values ranging from an average of 1758 kJ/(h·cow (500 kg)) in the former to 1600 kJ/(h·cow) (500 kg) in the latter.

(4) The ratio of latent heat to total heat in the exhaust air from the barns was approximately 0.40, ranging from 0.34 to 0.47.

(5) An average of 27% of animal sensible heat output was converted to the latent form by evaporation of moisture within the six barns. The average conversion in units with solid passageways was 28.7% and with slatted passageways 25.0%, at average barn temperatures of 8.4°C and 11.9°C, respectively.

(6) The temperature at which a free-stall barn is operated in practice would seem to have an influence on latent heat loads comparable to the manure-handling system.

(7) The largest statistical differences between the measured values and design data from the literature occurred in barn latent heat production.

(8) Statistically, the most significant difference between the heat production of barns with solid and slatted passageways was in their latent heat components.

RECOMMENDATIONS

The results of this study indicate latent heat loads in free-stall dairy barns exceed existing design data, and that manure-handling systems play a significant role in barn heat and moisture loads. Solid passageways have moisture loads that are higher than free-stall units with slatted passageways. Ambient temperature plays a major role in moisture loads.

Designers of ventilation systems for dairy livestock structures may wish to adjust design parameters. The validity of existing design data, particularly with respect to dairy housing type, should be questioned.

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