THE REDUCTION OF VENTILATION HEAT LOSS BY POROSITY

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ABSTRACT

Porous-inlet ventilation systems have been found to give satisfactory results in areas where winter temperatures drop to 0°C and below. An investigation was made on a large model building simulating the humidity and temperature conditions prevailing in animal housing during winter. Flax straw was employed as the material of the porous ceiling, since it is a material readily available in some areas. The ceiling porosity was reduced in various stages by placing perforated panels under the material. Tests were made with the naturally occurring convection, and also, comparative tests were made with an additional circulation fan installed.

The simultaneous heat and moisture transmission characteristics of the porous system were evaluated and compared with a similar but nonporous system.

It was shown that the porous ceiling inlet system performs better in conserving sensible heat than does the similar but nonporous system. The performance with naturally occurring convection is better than with additional forced convection.

INTRODUCTION

For many years, ideas on insulation, ventilation and vapor barriers have been constrained to one simple pattern of design - the air-tight insulated building, with vapor barrier and forced air ventilation. Naturally, this type of construction and ventilation system has been applied to agricultural buildings for housing animals.

By observing animal housing in severely cold conditions, it was realized that this system did not provide the optimum solution, as better results were being obtained in some buildings of a type of construction which contained some "porosity". Animal buildings are not normally provided with any heat, other than that derived from the animals themselves, so that, in this respect, the ventilation problem is unique. In the light of the increasing emphasis being placed on energy conservation, however, it is possible that the experience gained in agricultural buildings should be reexamined for application to other types of buildings.

Porosity in a building introduces new concepts. The flow of ventilating air through a porous material reduces the rate of heat conduction of the material.[1,2] Other porous materials allow diffusion of air, gases and moisture, without a loss of sensible heat as is the case with air exchange type of ventilation.[3] Air in a building such as an animal barn, is not a homogeneous mixture of air and moisture throughout its entire volume. If the air with greater moisture content can be evacuated rather than mixed, the amount of heat loss in ventilation is reduced. Air flow, distribution and mixing, due to natural convection or due to forced mixing, will have different effects on the heat loss attributed to ventilation. In animal housing the ventilation required is usually that necessary to control the relative humidity, which tends to be much higher than that encountered in other buildings.

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Test data on the characteristics of specific materials as porous ceiling inlets are required to assist in the acceptance of these new concepts into building design.

Flax straw was selected as a material which is plentiful in some regions, the tests being made on a 2.5m cubical model building. It is known that when a straw ceiling is employed in practice, it usually results in overventilation, as it does not offer enough resistance to the free movement of air through the ceiling. It was necessary then to explore the effect of partially blanking-off the air movement with perforated panels placed under the material. It was also considered possible to show in the model apparatus that introducing additional forced mixing would change the amount of heat lost in ventilation.

Description of Apparatus

The apparatus employed was a 2.5m cubical box, Fig. 1. The frame of the box was constructed from 90mm x 90mm wooden members. The vertical frame members at the four corners extended to the laboratory floor supporting the box about one metre above the floor. This clearance assures adequate air circulation under the box, keeping it at the same temperature as the ambient environment. Sheets of 12.5mm-thick plywood formed the walls and floor, A, of the box, leaving the top of the box open for installation of the experimental ceiling, B. A lining of plastic sheeting was applied to the four walls and floor to provide a vapor barrier, and to prevent air filtration through the walls and floor. Slabs of expanded polystyrene were glued to the outside surfaces of the walls and floor, forming a 100mm-thick layer of insulation. Wooden tie-bars at three levels along the box height were used to hold the insulating slabs in place, and to prevent any tendency for them to come off. The joints between the slabs were sealed with a caulking compound.

The box was centrally placed in a larger cubical chamber, leaving a one metre space around the box. All this was housed in a cold storage laboratory maintained at approximately 0^oC. By means of a system of ducts and a fan, air from the cold storage laboratory was circulated in the space around the experimental box. Air was drawn from this space at the top and entered at the bottom of the apparatus. This maintained a fairly constant temperature of about 0^oC in the space around the box.

Access to the interior of the box was through a small, snugly fitting door employing the same materials of construction as the box walls and situated in the floor of the box. During any experimental run this door was closed and its edges taped to the box floor to prevent air infiltration. Wooden beams were located near to the top of the box at approximately 400mm centers to support the experimental ceiling.

The filtration of air through the ceiling was effected by a fan situated outside of the box, drawing air from the box through a 7.5cm diam pipe. A steel drum, C, supported on a wooden stand, was positioned inside the box with its centerline about one metre above the bottom of the box. On one of its ends a 50mm-diam, 45^o sharp-edged orifice was fitted. The pressure drop across the orifice was measured by means of a water-filled micromanometer. The other end of the drum was connected to the ventilating air exhaust pipe. A rubber pipe connector was fitted to the pipe at the section where it passes through the wall to reduce heat conduction. The ventilation fan operated at constant speed and, to regulate the air flow rate through the orifice, a butterfly valve was installed in the outlet pipe.

To maintain a desired temperature and humidity level, a heater-humidifier, D, was incorporated. It consisted of a duct about one metre long, with a fan at one end, which forced air between four finned electrical resistance heater elements. At the other end, the heated air was forced through an evaporator element. Between the heaters and the evaporator element, two baffles were included, with which the amount of air through the evaporator and thus the evaporation rate could be controlled. This allowed various degrees of humidification inside the box to be achieved. Temperature control inside the box was possible through the use of various parallel and series connections of the four heater elements. It was possible to keep the temperature and humidity in the box within a close range throughout the duration of the investigation.

The water supply for the humidifier was from a 20-ℓ reservoir tank located within the box. The tank was filled through a plastic pipe running through the wall of the box to a filler funnel. A level mark on this tube facilitated accurate filling of the tank. The time between successive fillings and the amount of water added, provided an accurate measure of the evaporation rate. The water from the reservoir tank was conveyed into a smaller supply tank through a float valve which maintained a constant depth of water in the supply tank. The surface area of the supply tank was reduced to a small area around the float, to give more accurate measurement of water quantity. A submerged water pump in the tank circulated water over the evaporator element.

The electrical input, E, to the heaters, blower fan, water pump and circulating fan when operating, was supplied from a constant output voltage transformer located outside of the box. A calibrated watt-hour-meter was used to measure the total power input.

Temperature differences between the top and bottom of the box of up to 3.5°C were observed. When using the small hole inlet for nonporous ceiling tests, somewhat higher temperature gradients were observed than when filtrating air through the ceiling. An electric fan, F, was positioned near the center of the box and set to blow downwards. It had the effect of mixing the air and reducing the temperature gradient. For each of the ceiling configurations, tests were run with the circulating fan running and with the circulating fan not running.

The flax straw employed for the ceiling is a fine short-stalked straw. The length of the chopped straw averaged about 60mm and contained a lot of fine chaff which held the straw together in a continuous bed. In the installation of the ceiling, pieces of 1m-wide, 25mm chicken wire mesh were stapled to the wooden beams running across the top of the box, forming the support for the straw. The wooden beams provided a shorter span for the wire mesh strips, minimizing the amount of sagging when loaded. The straw was then evenly spread and at the same time "fluffed" on the wire mesh. Eighty kg of straw was spread on the ceiling to a depth of 250mm. This depth settled to about 200mm in about 4 days, after which very little change in ceiling depth occurred. The 25mm (1-in.) wire mesh was observed to hold the straw and also the chaff very effectively.

Samples of the straw were milled and the fine particles used in pycnometer tests to determine the specific gravity of the straw material. For the settled volume, and the measured value of specific gravity, the porosity of the ceiling was estimated. This was found to be 94% which, however, includes the void spaces between the straw stalks and pore spaces within the structure of the material not accessible to the filtrating air. The actual pore volume through which the ventilating air passes could not be determined. The 94% porosity value serves to indicate the highly porous nature of the straw ceiling.

Four thermocouple psychrometers were employed, their construction conforming to the conventional aspirated wet and dry bulb mercury thermometer psychrometer. The wet bulb junctions were covered with snugly fitting wicks, to a length of 30 to 50mm. The wicks were carried through plastic tubes to flasks of distilled water. The junctions were shielded against radiation with polished aluminum foil.

The psychrometers were employed to measure conditions outside of the box, at a point 300mm under the ceiling, at a point 300mm above the floor, and at the center height close to the air flow measuring orifice.

Dry bulb thermocouples were employed to measure the temperature at the center of the box and the temperature of the air in the exit pipe. The steady outside ambient temperature was determined by means of a thermocouple placed in a flask of oil, located outside of the box.

Seven thermocouples were set in the straw ceiling at points close to the mid depth to obtain the temperature at various points and to observe any temperature change due to air circulation that may be set up by convective currents through the ceiling.

At one point in the ceiling, selected at random, but closer to the center than to the edge, seven thermocouples were placed in the straw at equally spaced intervals of depth. The purpose of this arrangement was to determine the temperature distribution at various flow rates and in the various tests, even if only at one point.

The 25 thermocouples were read and recorded as required by a data acqusition system.

Order of Experiments

It was necessary to make a careful calibration of the equipment, as the heat loss through the ceiling is determined by deducting the heat to the ventilating air and the heat conducted through the walls and bottom, pipes and wires, from the total power input.

The calibrations were made using a 10cm-thick ceiling of fiber glass mounted on pegboard. Calibrations were made with the ceiling porous, when it is known that for this thickness of porous fiber glass ceiling and at the higher rates of ventilation, the heat loss by conduction is reduced to a negligibly small amount. This was confirmed by making the ceiling nonporous with a plastic sheet between the pegboard and the fiber glass and ventilating through a small opening. The insulating value of the ceiling then being known from suppliers data, the heat loss of the remaining surfaces, pipes and wires, could be determined, and an overall coefficient established. It was also shown by experiment that this coefficient is insensitive to temperature difference.

Following the calibration, the fiber glass ceiling was removed and the flax straw ceiling put in place.

Tests were run on the open straw ceiling, installed as described, at various flow rates. The inside temperature was maintained in the range 15 - 20°C. The steady state temperatures, power input, water evaporated and all the relevant data to calculate the steady state heat and mass balance were recorded. The heat loss and water transmitted through the ceiling were calculated in each case. Each test took about 2 to 4 days.

After running the tests with the open straw ceiling, the effective flow area through the ceiling was successively reduced in two stages and similar tests run. Masonite panels drilled with 50mm-diam holes in a square grid pattern, with 125mm center to center spacing were placed under the straw ceiling. This provided a flow area porosity through the panels of 12.5%. After tests with this arrangement, the panels were changed. This time the panels had 25mm-diam holes in the same pattern and center spacing. This gave a flow area through the panel which was 3.1% of the total ceiling area.

Lastly, solid masonite panels were installed in place of the perforated ones. This assured that no air filtration would take place through the ceiling from the inside to the outside or vice versa. A 100mm x 100mm hole was cut in the ceiling near to the edge of the box to allow entrance of ventilating air. Further tests were run at the same ventilation rates. The value of the heat transfer coefficient obtained in these tests was taken as the actual overall heat transfer coefficient of the straw ceiling when used as an insulation but not as a ventilation inlet.

RESULTS

Fig. 2 shows the results of the calibration test to determine the heat loss of the walls, floor, pipes and wires of the apparatus. U_b is the value which the overall heat transfer coefficient reaches as the infiltration rate is increased. $U_b = 0.285$ W/m^{2}K is the calibration of the apparatus for the purpose of determining the heat loss through ceilings to be installed later.

Correspondingly, Table 1 shows values of overall heat transfer coefficient for the flax straw ceiling, when it was made nonporous by placing solid panels on the underside. Air was then admitted for ventilation through one small opening. Results are shown both with and without the air circulation fan in operation: air circulation appears to have no effect. If the spurious result of 0.689 is eliminated, the average value with air circulation is 0.462 W/m^{2}K, and without air circulation 0.451 W/m^{2}K, giving an overall average of 0.456 W/m^{2}K. For the depth of straw employed, 200mm, this straw is evidently not a very good insulation material.

When filtration of air is present the performance of the material is based upon the sensible heat loss per unit mass of moisture evaporated and transmitted out of the box. This is compared with the sensible heat loss per unit mass of moisture removed in air exchange type ventilation as with a nonporous ceiling for the same inside and outside temperatures and relative humidities. The ratio of the one to the other is called the sensible heat loss factor F. The porous ceiling characteristically permits a high rate of heat loss: it also permits a high rate of escape of moisture. It is the ratio of heat loss to moisture loss that is important in animal housing, the problem being not only to conserve heat but to eliminate moisture. Conserving heat does not of itself provide the optimum result.

Figs. 3, 4 and 5 show the results obtained for all the tests on the porous straw ceiling in terms of the sensible heat loss factor F. A value of F = 1 signifies a heat loss equal to that of air exchange type ventilation. F less than one signifies that the heat loss is not as great as it would be with air exchange type of ventilation.

It should be clear that the porous inlet provides a superior performance. The first and most significant observation from these results is that the value of F is less than one, except in the case with the open straw ceiling with the air circulating fan operating.

The plots of the sensible heat loss factor against the infiltration rate clearly show the effect of the circulating fan. In all cases the value of F is found to be higher with the circulating fan running.

The best performance is at zero infiltration rate. As the infiltration rate is increased the value of F rises for all of the ceiling configurations.

Of all the ceilings tested, the open straw ceiling proved to have the worst performance. With the circulating fan running, the value of F obtained was higher than one in the whole range except at zero infiltration rate, where the value is just slightly less than one. However, without the fan, the ceiling shows an appreciable advantage with the value of F varying from about 0.7 at zero infiltration rate to 0.9 at higher infiltration rates.

The results for the straw ceiling with masonite panels of 12.5% porosity, as depicted in Fig. 4, show an improved performance from that obtained for the open straw ceiling. For low ventilation rates and with the circulating fan, the value of F is less than one but increases to above 1.0 for values of infiltration rate G above 2.70×10^{-3} kg/m^{2}s (2.0 lb/ft^{2}h). G is the net infiltration rate induced by the ventilation fan: there may be additional ventilation through a porous ceiling due to convective flows.

Without the circulating fan, however, the value of F is less than 1.0 for the whole range. At $G = 0$, the value of F is about 0.55 and this gradually increases to 0.9 at $G = 5 \times 10^{-3}$ kg/m^{2}s.

The results for the straw ceiling on masonite panels of porosity 3.1%, show a further improvement on the results of the straw on a panel of porosity 12.5%. The value of F is less than 1.0 for both the air circulation and no air circulation cases, for the whole range of infiltration rates. At $G = 0$, the value of F with the circulating fan running is approximately 1½ times as much as the value of F with no air circulation (0.72 and 0.5, respectively), but this converges towards a common value at higher infiltration rates. When G is greater than 4.7×10^{-3} kg/m^{2}s the value in both cases is about 0.9.

The converging tendency is evident in the results of the other two ceiling configurations, but is not as prominent as in the case of the straw on masonite panels of 3.1% porosity, indicating that as the infiltration rate increases the effect of air circulation becomes less, and in the limit has no effect at all. The air circulation fan evidently mixes the air and also increases the convection through the ceiling at low infiltration rates.

Although only three ceiling porosities were tested, the data obtained show very clearly that as the porosity was reduced, a ceiling with better performance in terms of the sensible heat loss factor results. Adding panels with low area porosity helped reduce the over-ventilating tendency of the ceiling, resulting in a better ventilation system. The panels also act as barriers to convective air flow through the ceiling, especially when the air circulating fan is operating.

TEMPERATURE IN THE CEILING

Monitoring the temperature at the various locations in the ceiling confirmed that considerable convective flow occurred at the lower infiltration rates.

Fig. 6 shows the temperature distribution over the depth of the straw, when the ceiling has been blanked-off with solid panels. The distribution corresponds to what would be expected of an insulation material, that is, the temperature gradient is constant, and independent of the ventilation rate.

Referring to Fig. 7, however, the typical result of air flow through a porous ceiling is shown. At low rates of infiltration the temperature is quite high throughout the material and up to the top surface, indicative of an upward convective flow at this particular location. At high infiltration rates the shape of the curve is reversed, showing a low temperature throughout most of the depth of the material, increasing sharply close to the inner surface, indicating a downward flow. A downward flow is more likely to occur at lower porosities and at higher infiltration rates. Convective flow, upwards in some areas, downwards in other areas, is more likely to occur at high porosities and at low infiltration rates.

PRACTICAL CONSIDERATIONS

It was not possible to control the humidity level in the box to one particular value for all of the tests. However, throughout the experiments the relative humidity was maintained within the range 68% to 90%. The extreme values were obtained with the open straw ceiling and high infiltration rates (68%) and with the blanked ceiling at zero ventilation rate (90%). Higher humidities were avoided as condensation would occur on the walls and make calculations of performance impossible. The humidity of the ambient environment was fairly steady as the cold storage room was maintained at constant temperature and at high humidity. No traces of condensation were observed within the box when the relative humidity was less than 90%. As the relative humidity is increased above 90%, condensation commences on the walls at the corners, and at about 95% relative humidity some condensation was observed on the masonite panels close to the perforations but none on the straw itself. However, at zero infiltration rate condensation was observed on the hair tips of the straw at the top surface of the ceiling. This was on an area of about 1m^2 close to one corner of the ceiling when the circulating fan was running. Without the circulating fan, the same general area and also the edges of the ceiling showed wet straw tips. The lower surface of the ceiling was found to be dry. On introducing the ventilating air, the droplets on the straw tips dried off in a short time.

The amount of moisture which must be removed from animal barns includes moisture evaporated from the stall, gutter and manger surfaces, although the greater part is the quantity released by the animals in respiration. The ventilation system must handle these amounts to keep the barn dry. Esmay[8] gives the moisture dissipation rates from dairy barns in the ambient temperature range 0 - 23°C as 0.25 to 0.70 kg/h per 450kg animal body weight: the required water vapor removal rates from hog houses with concrete floors is given as varying between 0.08 and 0.11 kg/h per hog in the same temperature range.

The floor area of the experimental box was designed to represent the size of an area in a barn which would be occupied by one large animal, (e.g. a 450kg cow), or several smaller animals. Estimates from the holding capacity of standard type swine housing indicate a maximum of three 60kg hogs in the area of the box. To evaluate the porous-inlet ventilation system in the practical range of interest, the amounts of water removed from this apparatus should compare with the amount of moisture which would be generated in the same area in an actual barn.

Fig. 8 shows the rate of water evaporation against the infiltration rate for the various tests on the various ceiling porosities. Except for the tests at zero infiltration rate, the evaporation rates for the other tests fall within the range 0.25 to 0.5 kg/hr. The range of moisture dissipation in a similar representative area in actual animal housing falls within the range 0.25 and 0.6 kg/h.

Tables 2, 3 and 4 show evaporation rates, sensible heat loss per kg moisture, and various temperatures, for all of the tests on the porous straw ceiling. The tests are numbered in the tables to correspond with the numbers shown at the points in Figs. 3, 4 and 5, respectively.

DISCUSSION

Although we tend to think of buildings as being air-tight insulated compartments and ventilation systems as being devices for positive air exchange with the outside, experience in animal housing, where heating is not usually employed, has brought to light some unexplored characteristics attributable to building porosity. In animal housing the problem is to control the moisture level without losing too much heat, as the source of heat is limited to the heat output of the animals. The usual ventilation system has a large heat loss per unit mass of moisture ventilated out. The porous building performs more favorably for a number of reasons. The filtration of the air required for ventilation through large areas of porous surface reduces the rate of heat conduction of this surface, hence the reason for convergence at $F = 0.9$ in Fig. 5. Also, this explains why the U_o value decreases to a constant value U_b, Fig. 2; the conductive heat loss through the porous fiber glass ceiling is decreasing to practically zero. A similar test with a nonporous fiber glass ceiling shows a constant value of U_o as would be expected. Porous materials permit diffusion of moisture, and moisture escaping from the building in this way does so with no loss of sensible heat, hence partly the reason for low values of F at zero infiltration in Figs. 3, 4 and 5. The air and water vapor mixture in a building is not a homogeneous mixture throughout its entire volume, consequently convective currents through a porous ceiling can eliminate moisture from the building for a smaller loss of heat than would be the case if the air is more thoroughly mixed, hence the reason for lower F values with circulating fan in operation, Figs. 3, 4 and 5. It is the interplay of these actions which is responsible for the favorable performance demonstrated for the porous flax straw ceiling as compared to the performance of air exchange type ventilation.

A flax straw ceiling of this depth, 200mm, is much too porous by itself and permits far too much ventilation by free natural convection. This confirms what has been found in practice when open straw or hay has been employed. The tests show that the ceiling can be blanked-off with perforated panels to at least as low a porosity as 3% to provide a practical solution. At this porosity the ceiling will perform quite well for practical purposes, although it is quite likely that a greater depth or different compaction, or other materials will perform better. The flax straw ceiling must be regarded as an example only, and not as an optimum solution.

CONCLUSION

1. The porous building and its ventilation system interact leading to lower heat loss for moisture control than is possible with the nonporous construction.

2. An open flax straw ceiling of 200mm depth would allow too much ventilation by free natural convection to be practically useful in animal housing.

3. Blanking-off the underside of the straw ceiling with perforated panels down to 3% porosity reduces free natural convection to a suitable level and gives a favorable performance.

4. When blanked-off at either 12% or 3% porosity, the ventilation heat loss in terms of sensible heat loss per unit mass of moisture ventilated out is much smaller than the sensible heat loss in air exchange type ventilation.

5. The effect of additional mixing of the air is to increase the sensible heat loss per unit mass of moisture ventilated out, with the porous ceiling ventilation system.

6. Flax straw at the depth of 200mm, does not provide good insulation compared with common insulation materials.

7. Following the example of this investigation there is need for a wide range of tests on this and other materials in order to find the optimum material and construction for porous ceiling inlet ventilation systems.

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Table 1 Overall Heat Transfer Coefficient U_α for the Nonpermeable Straw Ceiling

Ventilation rate (kg/s) x 10^2	U_α (W/m^2K) With air circulation	U_α (W/m^2K) Without air circulation
2.70	0.482	0.491
2.09	0.461	0.393
1.44	0.447	0.403
0.80	0.689	0.484
0.00	0.459	0.482

Table 2 Data for Open Straw Ceiling

	M_w (cc/h)	Q (kJ/kg)	t_c (°C)	t_c* (°C)	t_t (°C)	t_b (°C)
1	218	3540	19.37	16.81	20.05	18.46
2	208	3602	18.80	16.38	20.16	18.49
3	286	3800	19.53	16.11	20.83	19.23
4						
5	351	3940	16.90	14.0	18.29	16.78
6	356	3889	16.85	13.89	18.41	16.75
7	425	3566	18.22	14.36	19.86	17.83
8	446	3680	17.89	14.52	19.86	17.77
9	442	3420	16.82	13.22	18.85	16.79
10	500	3061	17.23	14.30	18.84	17.10
11	228	2556	17.13	15.03	17.64	17.56
12	296	3102	17.29	14.15	17.48	17.25
13	382	3150	17.44	14.07	17.70	17.39
14	420	3090	15.42	12.76	15.87	15.45
15	451	3550	15.05	12.22	15.52	15.13
16	540	3020	18.32	13.95	19.05	18.60

Numbers refer to points in Fig. 3

M_w	evaporation rate
Q	sensible heat loss per kg moisture
t_c	temperature at center of box
t_c*	wet bulb temperature at center of box
t_t	temperature at top of box
t_b	temperature at bottom of box

Table 3 Data for Straw Ceiling with 12.5% Porosity Panels

	M_w (cc/h)	Q (kJ/kg)	t_c (°C)	t_c* (°C)	t_t (°C)	t_b (°C)
1	200	2258	18.61	15.46	18.26	18.23
2	213	2063	18.75	15.45	18.46	18.12
3	240	2963	16.16	13.55	16.44	16.10
4	300	3219	18.49	15.53	18.56	19.00
5	296	3242	18.52	15.52	18.72	18.79
6	300	3811	15.99	12.41	16.28	16.05
7	372	4006	17.28	13.53	17.75	17.60
8	422	4116	17.34	13.83	17.33	17.32
9	436	4091	17.44	13.85	17.91	17.36
10	227	1680	20.01	17.57	21.07	19.68
11	229	2240	18.40	16.04	18.96	17.78
12	290	3120	17.49	14.16	18.68	17.43
13	426	3268	17.76	14.43	19.00	17.60
14	372	3300	16.69	12.41	18.28	16.70
15	424	3350	17.40	13.85	18.45	17.35

Numbers refer to points in Fig. 4

M_w	evaporation rate
Q	sensible heat loss per kg moisture
t_c	temperature at centre of box
t_c*	wet bulb temperature at centre of box
t_t	temperature at top of box
t_b	temperature at bottom of box

Table 4 Data for Straw Ceiling with 3.1% Porosity Panels

	M_w (cc/h)	Q (kJ/kg)	t_c (°C)	t_c* (°C)	t_t (°C)	t_b (°C)
1	102	1945	18.91	15.12	19.11	18.84
2	285	2020	18.07	15.64	18.31	18.03
3	312	2596	17.69	14.74	18.07	17.68
4	390	2987	16.97	14.41	17.78	17.33
5	424	3450	16.10	13.06	16.56	15.99
6	88	1703	18.30	14.52	19.4	17.82
7	261	1925	18.14	16.06	19.20	18.27
8	270	2103	18.7	15.7	19.73	18.53
9	305	2520	16.79	14.52	19.25	17.81
10	375	2752	17.64	13.89	18.8	17.7
11	395	3047	16.83	12.85	18.17	16.63

Numbers refer to points in Fig. 5

M_w	evaporation rate
Q	sensible heat loss per kg moisture
t_c	temperature at center of box
t_c*	wet bulb temperature at center of box
t_t	temperature at top of box
t_b	temperature at bottom of box

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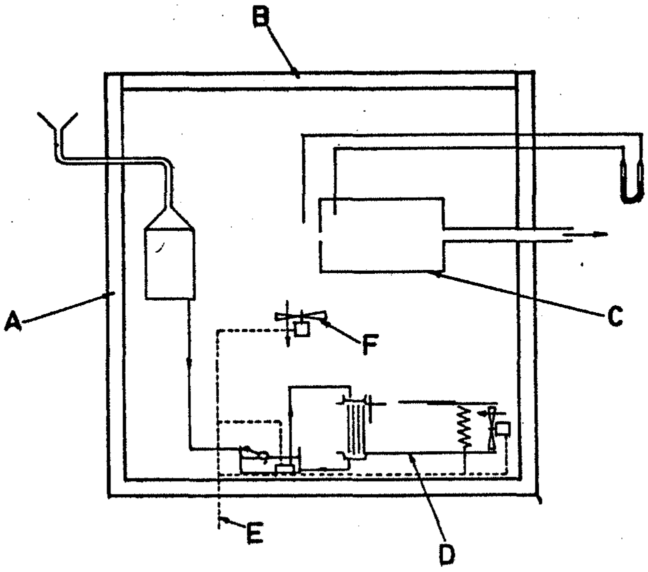

Fig. 1 Diagram of apparatus, a 2.5 m (8 ft) cubical box with ventilation system, heater and humidifier

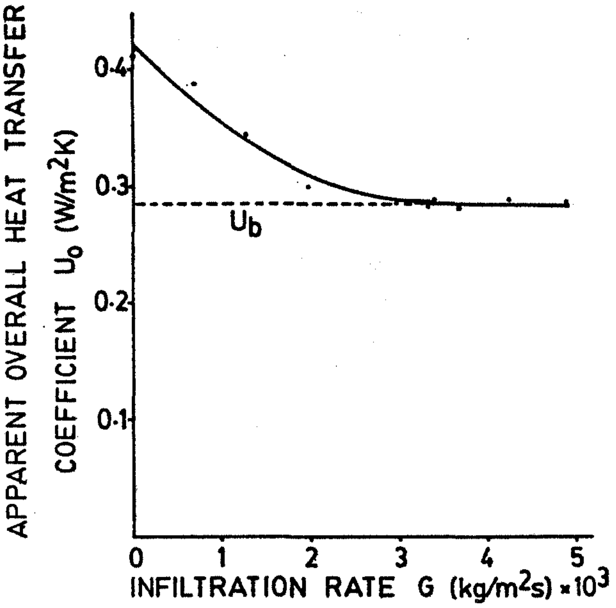

Fig. 2 Calibration for U_b with filtration of air through 10 cm fiber glass ceiling

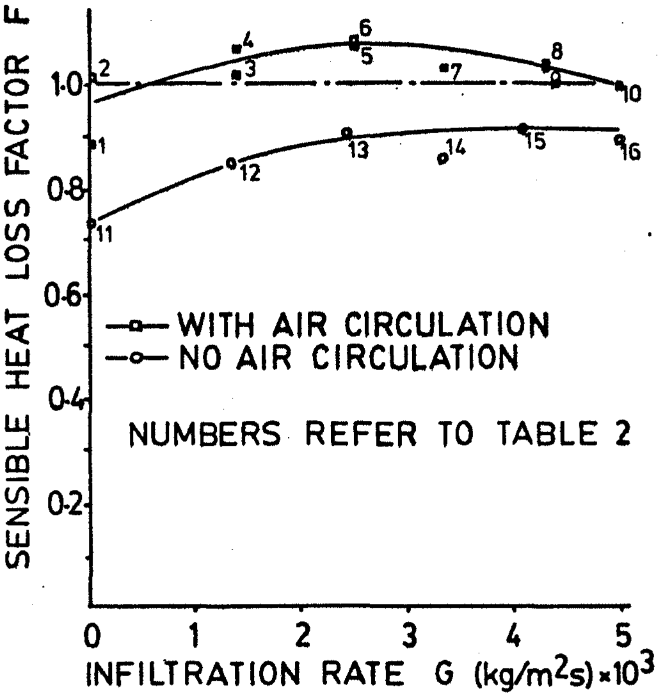

Fig. 3 Sensible heat loss factor vs infiltration rate for the open straw ceiling

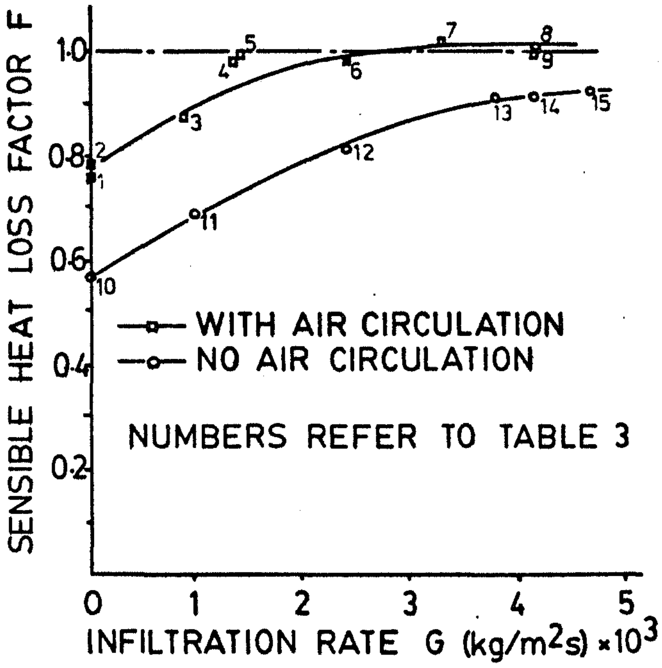

Fig. 4 Sensible heat loss factor vs infiltration rate for straw ceiling with 12.5% porosity panels

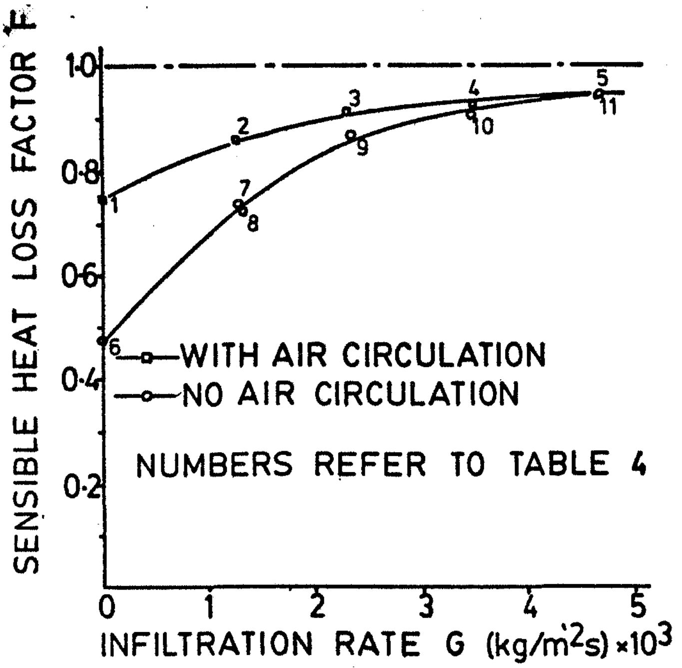

Fig. 5 Sensible heat loss factor vs infiltration rate for straw ceiling with 3.1% porosity panels

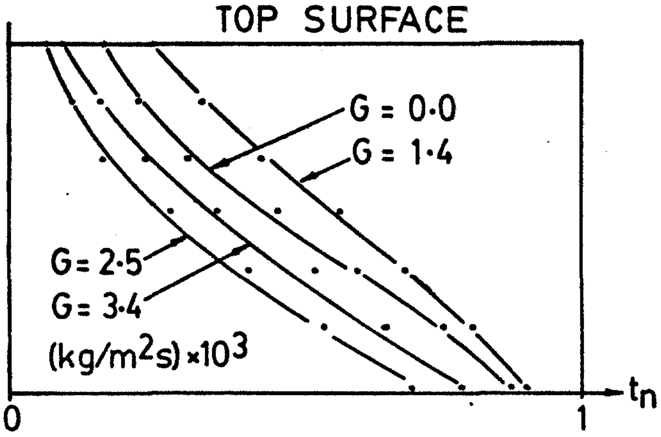

Fig. 6 Nondimensional temperature plots for various flow rates in the nonporous ceiling. Circulating fan not operating

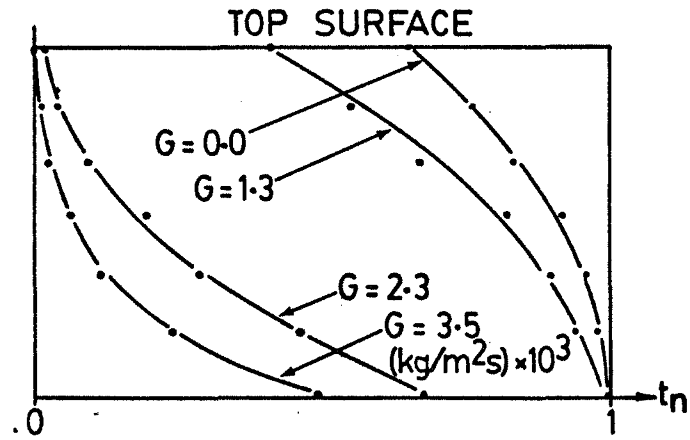

Fig. 7 Nondimensional temperature plots for various filtration rates with 12.5% porosity panels. Circulating fan not operating

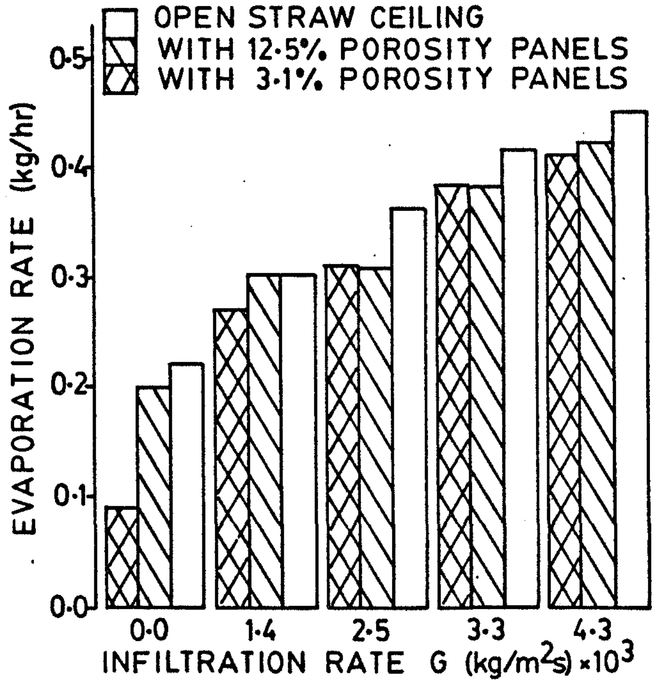

Fig. 8 Evaporation rate vs infiltration rate. Amounts are practically the same with or without circulation