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Convective Air Flow Effects with Mineral Wool Insulation in Wood-Frame Walls

Mineral wool batts are widely used as insulation in Canadian houses, especially between studs and other framing in wood-frame construction. Batts have commonly been adhered to a vapor barrier membrane, which also provided nailing flanges for fixing between framing, and have often been enclosed with a vapor-permeable membrane. In recent years, however, batts without attached membranes have become widely available and, in addition, the density of some of the mineral wool products has been greatly reduced. Material with sufficient inherent strength and rigidity without membranes offers some potential advantages in respect to the quality of installation. In considering the application of these materials, however, some questions arise in connection with the possibility of air flow through or within the insulation due to natural convection and the deleterious effects it might have on heat flow.

At the time these products were introduced, quantitative information on these natural convection effects, directly applicable to Canadian materials and house construction practice, was not available to the authors. Three situations in walls were envisaged:

(a) Insulation with both faces impermeable to air flow, that is, with no air space in contact with either surface of the mineral wool.

(b) Insulation having one face impermeable to air flow, with an air space in contact with the other face.

(c) Insulation having both faces permeable to air flow with an air space in contact with each face.

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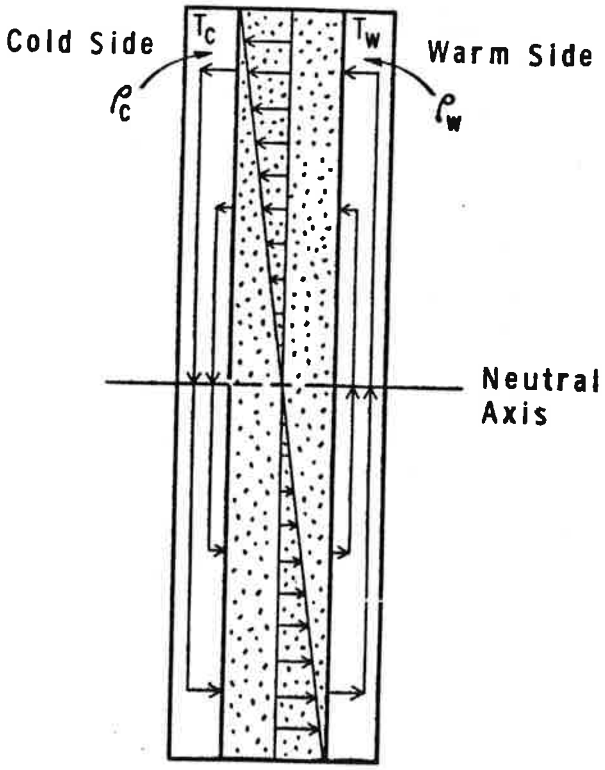
It was recognized that air movement, and its effect on total heat flow, will probably be small for cases (a) and (b), and this has subsequently been demonstrated[1]. In case (c), however, there is the possibility of a significant increase in heat flow from air flow through the insulation, due to air pressure differences on either side of the batt resulting from the difference in weight of the air columns. This is represented schematically in Fig. 1. As either continuous or discontinuous air

Fig. 1 Convective air flow in air spaces divided by air permeable insulation



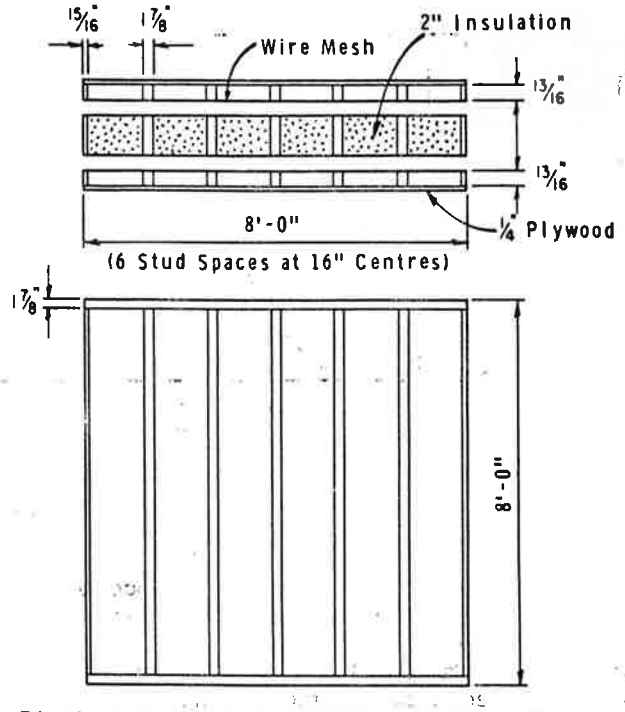


Fig. 2 Construction details of test wall No. 1

spaces could occur either by accident or intent, on both sides of a batt as installed, a test program was devised to determine the effects experimentally in the laboratory. The results are given in this paper. A companion paper[2] gives the results of a concurrent analytical study.

DESCRIPTION OF APPARATUS

Three basic walls were built for the test series. All were 8-ft sq and consisted of 2- by 4-in. pine studding, spaced at 16 in. on centers, faced on each side with 1/4-in. fir plywood. The studs of the first wall (Fig. 2) were built in three sections with the insulation located in the center section. One-in. hexagonal wire mesh was stretched across the outside sections. When the sections were brought together, the wire held the insulation in the center section at 2-in. thickness. The studs of the second wall were built in two sections, one 2-in. and the other 1 5/8 in. Wire mesh was attached to the latter section. The third wall, intended to simulate an arrangement that might readily occur in practice, was built with standard studs having dimensions 1-3/4 by 3-3/4 in.

Two types of glass fiber batt insulation, designated in this paper as A and B, both of 2-in. nominal thickness, were used in the measurements. The density of type A material was between 0.8 and 0.9 lb/cu ft; that of type B was between 2.0 and 2.5 lb/cu ft. The average fiber diameters of the two insulations, as determined by microscopic measurements, were 40 and 37 x 10^{-5} in., respectively.

Twelve panels were tested incorporating the two types of insulation in the three different wall constructions, both with and without polyethylene sheeting at one or both surfaces of the insulation

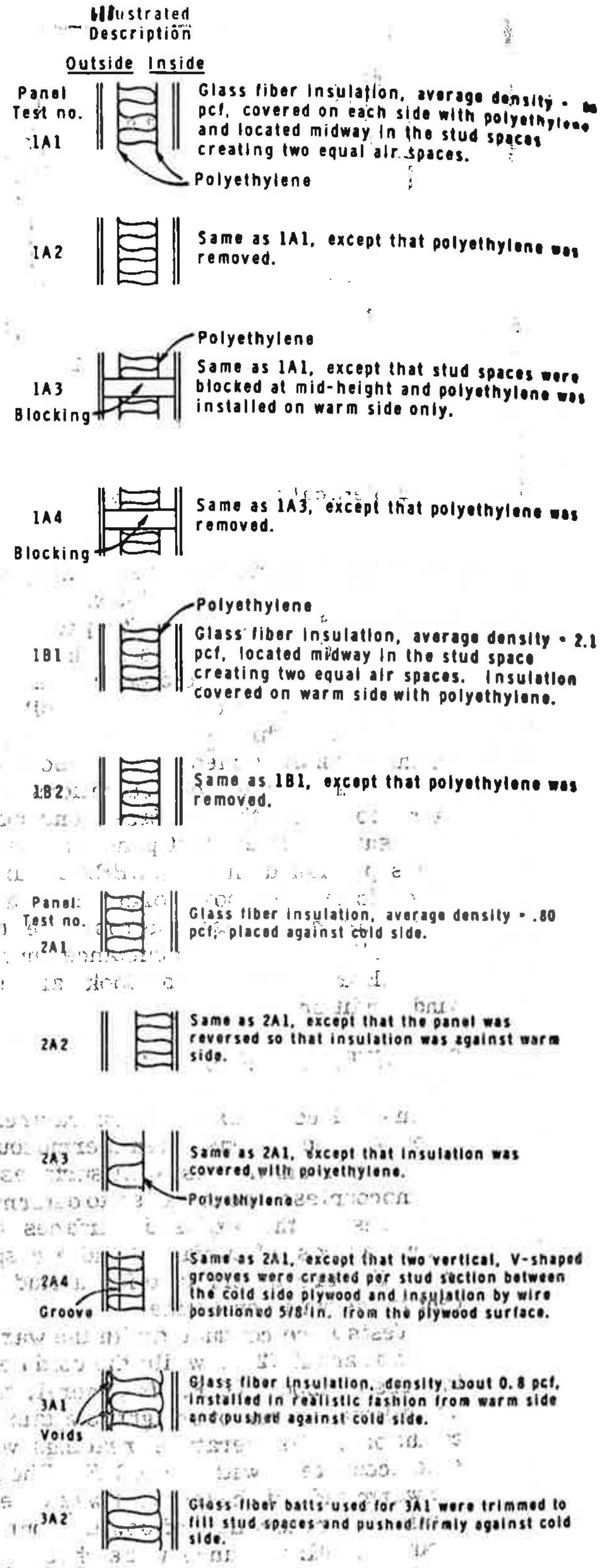


Fig. 3 Test wall code

to prevent air interchange between the insulation and the air spaces. The various panels were coded in accordance with the wall number, the designation A or B indicating the type of insulation, and an arrangement designation as given in Fig. 3.

Heat transmission through the various test panels was measured with the wall panel test unit

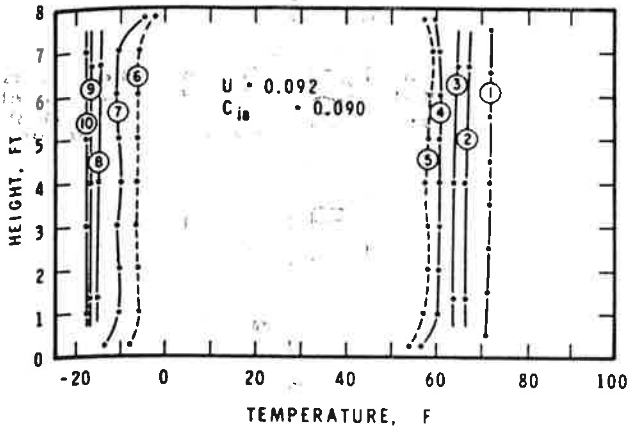


Fig. 4 Vertical temperature profiles, panel 1A1

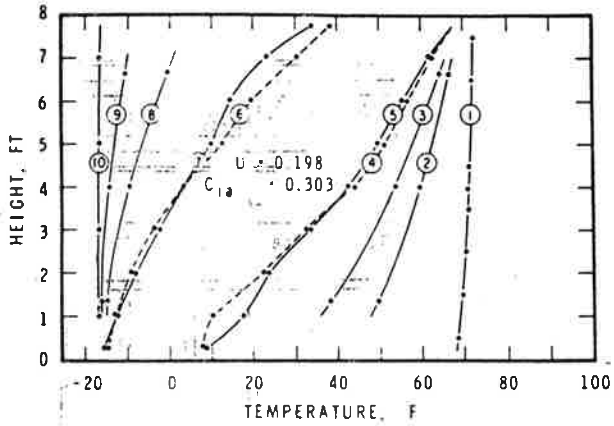


Fig. 5 Vertical temperature profiles, panel 1A2

previously described.[3] Basically, the apparatus consists of a cold-box/hot-box combination; each box is 4 ft deep with an 8-ft sq test opening. Panels lining the inside walls are heated in the warm box and cooled in the cold box by circulating liquid. The warm box liquid can be controlled between 65 and 75 F to within ± 0.01 F. The cold box temperature can be varied down to about -25 F.

Natural convection conditions exist in the warm box, and the surface conductance on the warm surface of the test panel agrees closely with values published in the ASHRAE Guide And Data Book. In the cold box, forced circulation of air is maintained horizontally across the test surface; the resultant surface conductance approximates the ASHRAE Guide And Data Book value of 6.00 for a wind condition.

EXPERIMENTAL PROCEDURE

Warm- and cold-box air temperatures were measured by copper-constantan thermocouples located about 3 in. from the test wall surfaces. Additional thermocouples were installed to determine the temperatures of the exposed surfaces of the wall. Temperatures of surfaces and air spaces within the wall were determined for a stud space adjacent to the wall centerline.

Tests were conducted with the warm box maintained at about 72 F, while the cold box was varied in steps to about -20 F. In general, the apparatus was allowed to run overnight to attain steady-state conditions. Temperature readings were considered accurate to within ± 0.1 F. The heat input to the warm side of the test unit was determined from continuous recordings of power input, accurate to about 1%. All readings were checked by a second set taken several hours after the first.

TEMPERATURE GRADIENTS

Representative vertical temperature profiles at various locations through the wall at the centerline of the instrumented stud space are given in Figs. 4 to 9. The numbering code used to identify the different temperature curves is presented in Table I.

Panels 1A2, 1A4 and 1B2, with insulation located midway in the stud space and without polyethylene covering, exhibited large vertical temperature variations in comparison with any of the panels in which there was no air space in contact with either surface or both surfaces of the insulation. These large variations are consistent with the pattern of air movement indicated in Fig. 1. Cold air moves through the insulation to the warm air space below the neutral axis, thereby lowering the warm-side temperature. An opposite air movement and temperature effect occurs above the neutral axis. In panel 1A4 this is evident both below and above the blocking at midheight.

The temperature patterns for panel 1B1 with the higher density insulation did not differ significantly from those for 1A1 (Fig. 4). The patterns

Table I. Identification of Temperature Curves in Figs. 4 to 9

Curve number	Location
1	Warm-side air
2	Exterior surface of warm plywood
3	Interior surface of warm plywood
4	Warm-side air space
5	Warm surface of insulation
6	Cold surface of insulation
7	Cold-side air space
8	Interior surface of cold plywood
9	Exterior surface of cold plywood
10	Cold-side air

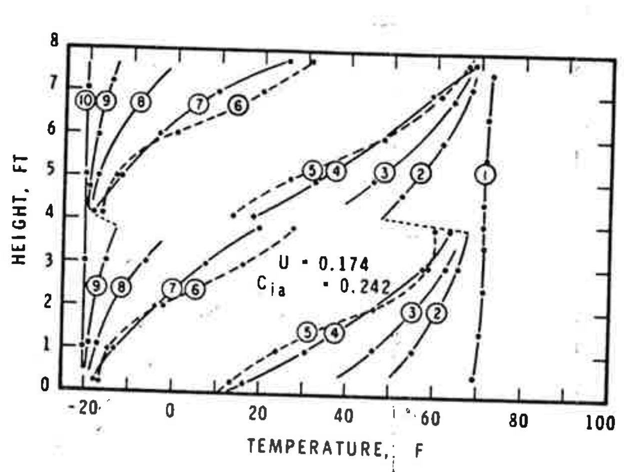


Fig. 6 Vertical temperature profiles panel 1A4

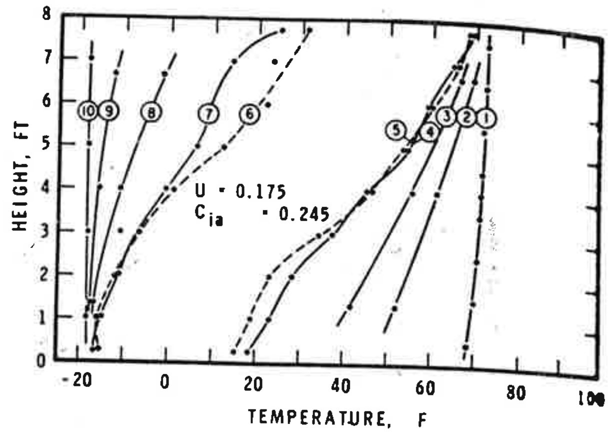


Fig. 7 Vertical temperature profiles, panel 1B2

for panel 2A3 were essentially the same as for 2A1 (Fig. 8): with the insulation pushed tightly against the cold-side sheathing, temperatures were the same whether or not the warmside air space was in contact with the insulation; temperatures on the cold side of the insulation were quite uniform but there were sharp temperature gradations on the warm side near the bottom due to air space convection. In panel 2A2, temperatures were uniform on the warm side but, as would be expected, temperatures increased toward the top of the air space on the cold side. Temperature patterns for panel 2A4 indicate the effect of some air flow through the insulation due to the presence of the 5/8-in. vertical grooves in the insulation on the cold side.

The surface temperature of the insulation rose slightly above the air space temperature on the warm side above the neutral axis in panels 1A2, 1A4 and 1B2 (Fig. 5). Air moving into the insulation tends to maintain the surface temperature of the insulation at the air temperature, in effect eliminating the usual convective boundary layer. Heat gained by radiation from the plywood surface then causes the temperature of the insulation surface to rise above that of the adjacent air. In addition to its effect on heatflow, the air exchange between air spaces on either side of the insulation results in a significant lowering of the inside surface temperatures near the bottom of the wall.

HEAT TRANSMISSION VALUES

The overall heat transmission coefficients (U values) for the various panels and apparent thermal conductances for the insulation plus air spaces in the region between studs (C_{ia} values) are presented in Figs. 10 and 11, respectively. U values were calculated from the following:

$$U = \frac{q_t}{A\,(T_i - T_o)}$$

where

q_t = total measured heat transfer rate, Btuh

A = overall area of panel, sq ft (64)

T_i = equivalent warm-side temperature, F

T_o = cold-side air temperature, F

Fig. 8 Vertical temperature profiles, panel 2A1

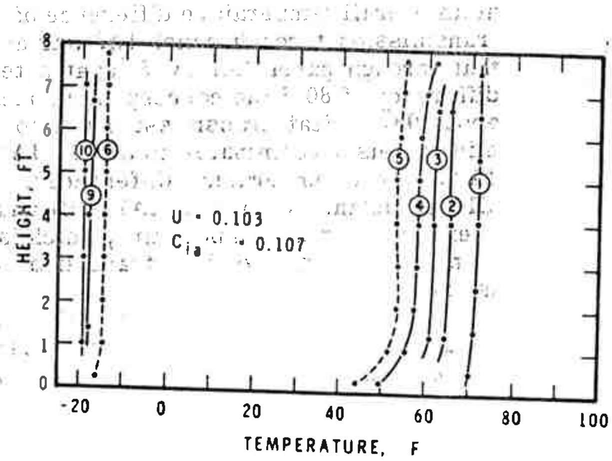
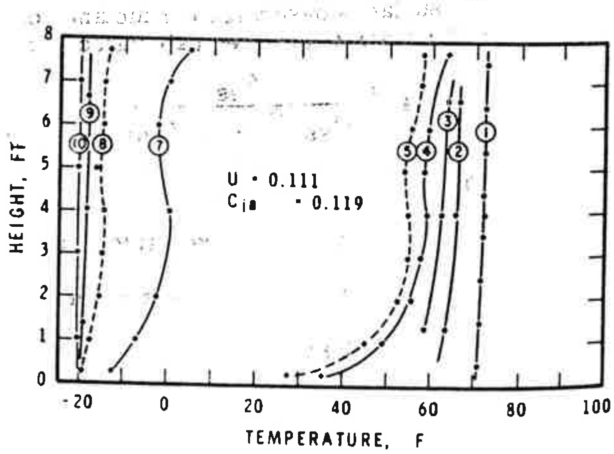


Fig. 9 Vertical temperature profiles, panel 2A4



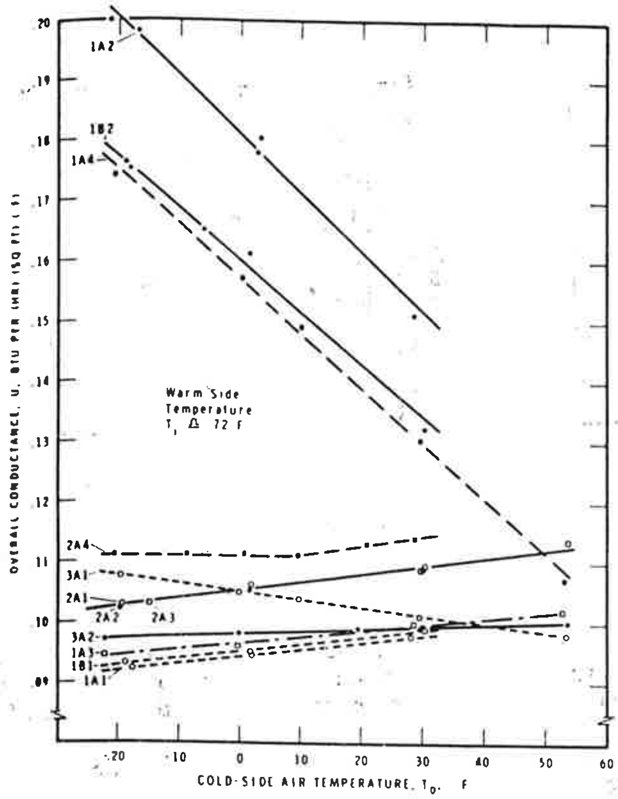


Fig. 10 Overall thermal conductance of panels

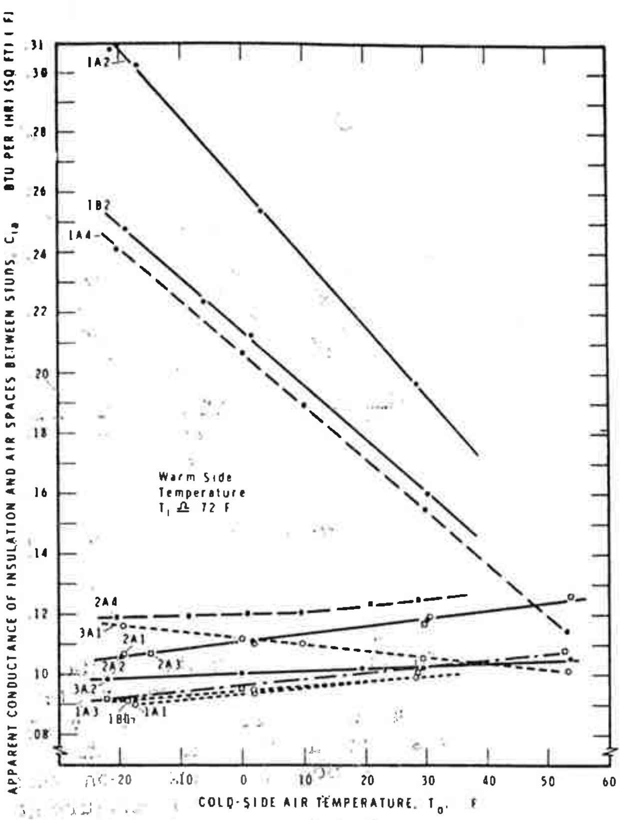


Fig. 11 Thermal conductance of insulation plus air spaces between studs

The equivalent temperature, T_i, falls between the temperature of the inner surface of the warm box and the warm-side air temperature, and was determined by the method previously outlined.[3]

In estimating the apparent conductance of the insulation and air spaces between the studs, C_{ia}, the heat flow through the region of the studs, q_s, was calculated on the basis of one-dimensional heat flow from the average of temperature measurements over the centerline of the studs at warm and cold surfaces, the cross-sectional area of the studs, and an assumed thermal conductivity for the studs and plywood of 0.8 Btu/hr, sq ft, F/in. The heat flow through the space between studs was then taken as:

$$q_{ss} = q_t - q_s \qquad (2)$$

The surface-to-surface conductance of the region between studs was then calculated as:

$$C_{ss} = \frac{q_{ss}}{A_{ss}\,(T_{si} - T_{so})} \qquad (3)$$

where

A_{ss} = wall area exclusive of studs, sq ft

T_{si} = average inside surface temperature between studs, F

T_{so} = average outside surface temperature between studs, F

The apparent conductance of the insulation and air space between studs, C_{ia}, was then obtained from C_{ss} by accounting for the thermal resistance of the plywood.

The heat-transfer rate increase due to the presence of continuous air spaces in contact with both sides of the insulation can be seen from Figs. 10 and 11, by comparing the results for panels 1A2, 1B2 and 1A4 with those for panels 1A1, 1B1 and 1A3. The increase is due to air circulation between the two spaces, through the insulation. The influence of this air flow increases with increasing overall temperature difference. For example, at an overall temperature difference of 40 F. heat transmission through panel 1A2 was greater than that through panel 1A1 by 51%; at a temperature difference of 80 F the corresponding increase was about 98%. Heat transmission due to convection effects thus predominates in panels 1A2, 1B2 and 1A4 at these temperature differences. The overall conductance of panels 1A1, 1B1 and 1A3 decreased with mean temperature, which is in agreement with theory when heat transfer by conduction is preponderant.

Overall conductance values, U, and apparent conductance values of the insulation and air spaces between studs, C_{ia}, are compared in Table II at an

Table II. Conductance Values of Panels Having Two Equal Air Spaces Separated by Insulation with and without Polyethylene Covering
t_{ao} = -20 F, $\Delta t_{overall}$ = 92 F

Panel	Conductance Btu/hr, sq ft, F		Ratio of conductance without and with polyethylene	
	U	C_{ia}	U ratio	C_{ia} Ratio
1A1	0.092	0.090		
1A2	0.200	0.309	2.18	3.44
1A3	0.094	0.092		
1A4	0.174	0.242	1.85	2.63
1B1	0.092	0.091		
1B2	0.178	0.249	1.93	2.74

Table III. Comparison of C_{ia} Values Derived from Measured Heat Flow and from Theory

Panel	Cold-side temperature t_o, F	Theoretical C_{ia} values based on C_{cc1}	C_{cc2}	Experim C_{ia} valu based o heat flo
1A2	28.6	0.15	0.19	0.20
	3.4	0.18	0.24	0.25
	-16.8	0.20	0.27	0.30
	-21.3	0.20	0.28	0.31
1B2	30.3	0.13	0.15	0.16
	1.7	0.15	0.20	0.21
	-6.0	0.16	0.21	0.23
	-18.1	0.17	0.24	0.25
	-18.7	0.17	0.24	0.25

overall temperature difference of about 92 F. Panels 1A1 and 1B1 incorporating types A and B insulation having average densities of 0.86 and 2.1 pcf, respectively, had about the same U and C_{ia} values when tested with polyethylene covering. When the polyethylene covering was removed, however, convection effects caused the U and C_{ia} values to increase by factors of 2.18 and 3.44 for type A insulation, while the corresponding factors for type B insulation were 1.85 and 2.63. The larger increase for type A insulation is attributable to its lower air flow resistance. Air flow coefficients were 2650 and 1680 cu ft/ hr, sq ft (lb/sq ft pressure difference) for types A and B insulation, respectively, at the 2-in. thickness.

The effect of horizontal midheight blocking in the stud spaces can be seen by comparing results for panels 1A3 and 1A4 with those for panels 1A1 and 1A2, the latter having no blocking. For tests in which the insulation was covered with polyethylene, blocking resulted in a slight increase in the U and C_{ia} values. In corresponding tests without polyethylene over the insulation, blocking resulted in a significant decrease in the U and C_{ia} values (compare 1A2 and 1A4 in Table II). For similar test conditions, midheight blocking will reduce the maximum pressure difference across the insulation by one-half. Consequently, the convective air flow and associated heat-transfer rate will be correspondingly reduced. Since air convection is the major factor contributing to heat transfer, a significant reduction in total heat flow results.

The close agreement in heat-transfer coefficients for panels 2A1, 2A2 and 2A3 in Figs. 10 and 11 indicates that no significant air interchange occurred between a single air space and permeable insulation, in contrast to the situation with air spaces on either side of the insulation. Panel 2A4 (similar to panel 2A1 except that in each stud space two V-shaped grooves, 5/8 in. deep, were introduced between the cold plywood surface and the insulation) had higher thermal conductance values than 2A1 at all cold-side temperature conditions. The flattening of the curve for panel 2A4 indicates the increased convection effect as the cold-side temperature decreased.

In preparing panel 3A1, a polyethylene film was stretched across the outer face of the studs and the batts were pushed toward the outside of the stud space in a manner intended to represent a realistic installation. The insulation was slightly wider than the stud space, which is normal with friction-fit material, with the result that it did not contact the polyethylene uniformly. A random pattern of narrow air spaces, more or less discontinuous, thus occurred between the polyethylene and the insulation, and could be viewed through the polyethylene with the outside plywood sheathing removed. The thickness of the nominal 2-in. insulation, on expanding in the stud space, was sufficient to bring it into contact with the inside plywood at several points. The negative slope of the curves for panel 3A1 in Figs. 10 and 11 indicates the occurrence of some convective effects.

Panel 3A2 was similar to panel 3A1, except that the voids on the cold side were largely eliminated by trimming the insulation batts to fit the stud spaces accurately. The positive slope of the 3A2 curves in Figs. 10 and 11 indicates that no significant air interchange occurred. The slightly lower conductance of panel 3A1 at the higher cold-side temperature may be due to the reduction of convection effects at small temperature differences and the thermal resistance presented by the voids on the cold side of the insulation.

TEST RESULTS COMPARED WITH THEORY

In the companion paper,[2] relationships are developed for the heat transfer through air permeable insulation installed in a vertical wall with continuous air spaces on both sides. Two models are considered. In the first, the air temperature in each air space is assumed uniform. The heat transfer due to fluid (air) conduction and convection (air flow through the insulation) is then defined as:

$$q = C_{cc1} W H (T_w - T_c)$$

where

C_{cc1} = an apparent heat-transfer coefficient for combined fluid conduction plus convection in the insulation

W and H = width and height of air spaces

T_w and T_c = temperature of air spaces on warm side and cold side, respectively

In the second model, the temperature in the air spaces varies linearly with height. The heat-transfer coefficient due to combined fluid conduction plus convection in Eq (4) is then designated C_{cc2} and the air space temperatures refer to average values.

From the equations given in the companion paper,[2] values off C_{cc1} and C_{cc2} were calculated for panels 1A2 and 1B2 at the various test conditions. These panels had 2-in. thick insulation located at the center of the stud spaces with air spaces on either side. The fluid properties were determined at mean temperatures of the air spaces. Values of C_{cc2} were based on the average temperature difference from top to bottom of the air spaces.

Determination of C_{cc1} and C_{cc2} required a knowledge of the air-flow coefficients of the insulation. These were determined by careful measurements on 1-ft sq specimens of both types of insulation. The flow rates were linear with pressure difference at the small pressure differences involved. At a fixed pressure difference, the flow rates varied inversely as the product of thickness and density for a specific insulation. Air-flow coefficients obtained were 5300 and 3360 cu ft/hr, sq ft, (lb/sq ft pressure difference)/in. of thickness for insulations A and B having densities of 0.86 and 2.1 lb/cu ft respectively.

To calculate the apparent conductance of insulation plus air spaces on both sides, it is necessary to make an estimate of the air space conductances; an average of 1 Btu/hr, sq ft, F was taken from values in the ASHRAE Guide And Data Book. In calculating the total heat transfer through the insulation, the component of the conductance due to radiation and fiber conduction, C_{rf}, must be added to C_{cc}. The apparent conductance of the insulation plus air spaces is then given by:

$$C_{ia} = \frac{1}{1/C\left(_{cc} + C_{rf}\right) + 2}$$

The results of these calculations, using values of both C_{cc1} and C_{cc2} are summarized in Table III, and are compared with values of C_{ia} derived from the heat flow measurements, using Eq (3). Theoretical values based on C_{cc2} are in better agreement with experimental values than those based on C_{cc1}.

CONCLUSION

Measurements reported in this paper demonstrate the increase in heat transfer due to convective air flow that can occur in wood-frame walls containing air-permeable mineral wool insulation with air spaces in contact with both sides. The effect of this air interchange between the air spaces increases with increasing temperature difference, air space height and air permeability of the insulation. Use of mid-height blocking and higher density insulation thus resulted in some reduction in the heat flow through the insulation, although convective effects were still significant.

With the 2-in. thick insulation, convective air flow effects were negligible when the insulation was isolated from the air spaces by an impermeable membrane, or when at least one of the air spaces was eliminated, for example, by installing the insulation firmly against the sheathing. When installed against the sheathing in a realistic manner, some small convective effects were noted. This emphasizes the desirability of careful installation, especially when the material does not completely fill the stud space. If it is not possible to ensure that air spaces will not occur on both sides of the insulation, an airtight membrane in contact with the insulation should be used.

Although the measurements reported in this paper have been for air-permeable insulation, it should be noted that similar convective effects can occur with impermeable materials with air spaces on either side if joints and boundaries are not airtight.

Good agreement was obtained between convective air flow effects derived from the wall heat flow measurements and those predicted from the theory presented in the companion paper.[2]

ACKNOWLEDGMENT

This is a contribution from the Div of Building Research, National Research Council, Canada, and is published with the approval of the Director of the Division.

REFERENCES

1. Lotz, W.A., Heat and Air Transfer in Cold Storage Insulation, ASHRAE Transactions, Vol. 70, pp. 181-188 (1964).

2. Wolf, S., A Theory for the Effects of Convective Air Flow Through Fibrous Thermal Insulation, To be presented at the ASHRAE 73rd Annual Meeting, Toronto, June 27-29, 1966.

3. Solvason, K.R., Large-scale Wall Heat-flow Measuring Apparatus, ASHRAE Transactions, Vol. 65, pp. 541-550 (1959).

4. Verschoor, J.D. and P. Grebbler, Heat Transfer by Gas Conduction and Radiation in Fibrous Insulations, ASME Transactions, Vol. 74, Number 6, pp. 961-968 (1952).

DISCUSSION

W. A. LOTZ, Granville, Ohio (Written): Mr. Wilson, Mr. Wolf and Dick Solvason are to be congratulated on a fine paper. The information presented in this paper is a welcome extension to the paper I published in 1964 and the work published by I. Hoglund in 1963 and 1964.

Have you had the opportunity to study the several papers on this subject published by the National Swedish Council for Building Research?

The conclusions developed from your research agree with those reached by myself and those of Hoglund on the effects of air currents in fibrous thermal insulation. In the few cases where the order of magnitude of our test results differs, I believe it is due to the differences in our test configurations and the type, thickness and fiber size of the insulations tested. Changing these variables can make large numercial changes in the test results. This point can be shown by a literature search on the many papers that have been published to prove an author's point.

As your paper and several other papers have shown, the thermal performance of permeable fibrous insulation is highly dependent on the building design and the insulation application technique.

AUTHOR WILSON: I very much appreciate Bill Lotz' comments, especially since they give me an opportunity to refer to the work of Dr. Hoglund in Sweden.

The work that we reported here was carried out in 1962 and 1963, and the original drafts of these papers were prepared in 1964. It wasn't until we had the pleasure of having Dr. Hoglund spend this last year with us as a visiting scientist that we were aware of his work.

He has made some significant studies partly in the area covered by these two papers and, in addition, has given consideration to the effects of forced convection air flow through insulation due to wind action on buildings.