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THERMAL PERFORMANCE OF FRAME WALLS

by

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Thermal Performance of Frame Walls

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SUMMARY — A preliminary study has been made of the effects of convection in insulated and uninsulated walls containing air spaces. Data are presented which illustrate the vertical variation in temperatures and heat flow rates existing in frame walls, when the insulation is ideally applied, and when openings occur at the top and bottom of insulations installed to form two air spaces.

In the study of the thermal performance of the exterior walls of buildings under winter conditions, certain assumptions have been made to permit the application of simple theory based on uni-directional heat flow perpendicular to the wall. This has resulted in an approach to wall analysis from an *overall average* point of view, conditions being assumed to be uniform in the plane of the wall. Little attention has been given to departures from these uniform conditions resulting from the influence of convective heat transfer in walls with air spaces.

Fig. 1 illustrates the possible effects of convection in the air space of a simple wall. Air in the space in contact with the warm side will become heated and will rise, increasing in temperature as it flows upward. Air next to the cold side of the space will lose heat and will fall, becoming progressively cooler at it descends. The circulation of air thus established within the space will result in a vertical variation in air temperature adjacent to the two bounding surfaces which, for purposes of discussion, may be represented by the curve in the figure.

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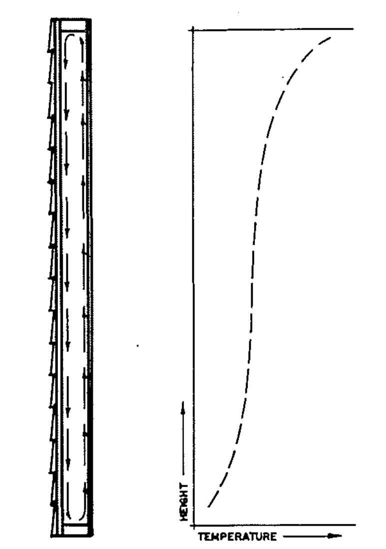

Fig. 1—Convection in air spaces

If it is assumed that ambient air temperatures are uniform over the wall, and that film resistances are constant with height, the rate of heat flow into the wall will be proportional to the air-to-air temperature difference across the inside sheathing. The rate of heat flow into the wall will therefore decrease with height. Similar reasoning may be applied to demonstrate that the rate of heat flow out of the wall, across the outside sheathing, will decrease from top to bottom.

It is more than likely that ambient air temperatures on the warm side of a wall will also increase with height, however, thus tending to produce a still greater variation in air space temperatures. In addition, the film coefficient for natural convection from heated surfaces increases with height up to 2 ft and varies as the 5/4 power of the temperature difference, as shown by Wilkes and Peterson[1]. This variation in film resistance may also contribute to increased variation in the rate of heat flow into the wall.

A still more serious condition may exist in walls insulated with foil curtains or blanket-type insulations where more than one interior air space is formed. When such insulations are installed in practice, it is unlikely that they are always sealed to surrounding structural members, particularly at the top and bottom. Even very small openings will permit

[1]Exponent numerals refer to References.

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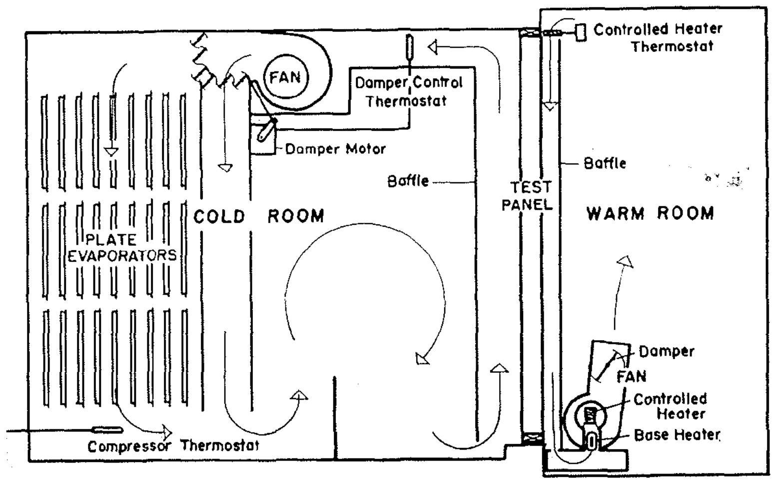


Fig. 2—Cross sectional view of wall panel test apparatus

air circulation between the two spaces since most of the air movement adjacent to a heated or cooled surface takes place within a fraction of an inch. If such a circulation exists, the intermediate membrane serves only as an interceptor of radiant heat, and is essentially by-passed by convection. Depending on the extent to which radiant heat energy is absorbed and transmitted across the spaces, sheathing temperatures will be lower than if no insulation were present and air circulation may be increased. In such cases, an even greater vertical heat flow variation may be experienced.

In addition to these possible effects, the presence of gaps in intermediate membranes will result in an increase in overall heat transfer. This effect has been demonstrated by Rowley et al[2] for blanket type insulations, an increase of 53 percent in overall heat transfer being reported when intentional gaps 1 in. in height were left at the top and bottom of the insulation.

The present project was initiated by the Division of Building Research of the *National Research Council of Canada*, in cooperation with the University of Saskatchewan, to determine the importance of convection effects in standard frame walls with air spaces. The work is being carried out at the Prairie Regional Station of the Division at Saskatoon and this paper presents the results obtained to date.

Test Apparatus

A cross-sectional view of the test apparatus employed is illustrated in Fig. 2. It consists of a cold room-warm room combination in which panels up to 8 ft in height and 7 ft in width may be subjected to steady state heat flow conditions. The refrigeration equipment for the cold room includes a nominal 5-ton, single-stage, water-cooled condensing unit using Freon 22 as the refrigerant. Three banks of nine plate-type evaporators are installed in the cold room, arranged in a unit as shown in Fig. 2. With this equipment, temperatures approaching −40 F may be maintained in the cold room, with a warm room temperature of 70 F.

Forced circulation of air is provided over both sides of the test panel in the direction of natural air movement. This air flow is confined by a baffle on each side so that more uniform velocities over the panel surfaces are provided. On the warm side, fans and heating equipment are mounted on this baffle and the whole assembly is hung from an overhead track so that it may be swung away to provide access to the test panel.

Control of air temperature in the cold room is accomplished by on-off operation of the condensing unit in accordance with the temperature of the air leaving the evaporator, coupled with a modulating by-pass damper arrangement responding to the temperature of the air leaving the panel surface. This control arrangement results in air temperature over the panel being maintained to within 1 F.

Temperature control in the warm room is provided by on-off operation of electric heaters supplemented by a manually-controlled base heater. A sensitive bi-metallic thermo-regulator is used as a controller, operating the heaters through an electronic relay. The base heater is adjusted manually using a variable voltage transformer. Air temperatures are controlled to within ½ F with this arrangement.

Copper-constantan thermocouples are employed for all temperature measurements, using a precision potentiometer. Heat meters are used to determine heat flow rates, the thermopile emf being recorded with a chart recorder. In order to use this instrument for the purpose, a constant-temperature bias thermocouple is included in the circuit. All thermocouple and heat meter leads are carried outside the apparatus and connected to a master switchboard.

A track is provided on the baffle covering the warm side of the panel in which a sliding heat meter support may be moved by an external cord. This support carries the heat meter by four spring loaded polystyrene rods which press the meter firmly against the wall surface when the baffle is in place. In this way a single heatmeter is employed to traverse the height of the wall.

Test Procedure

A single, basic wall panel 8 ft in height and 5 standard stud spaces in width was used throughout the tests. The various insulations tested were installed only in the three center stud spaces of this panel. Measurements were confined to the center space with the two adjacent spaces serving as guard areas. The 4- by 8-ft plasterboard sheet covering these stud spaces was secured with wood screws so that it could be removed to alter or replace the insulation for the different tests.

In conducting a test on each sample wall, air temperatures on the warm and cold sides of the panel were brought to the desired level and were maintained at this point until constant temperature conditions prevailed throughout the wall. Under these steady state conditions, a heatmeter traverse was made, the meter indications being recorded for a half hour period at each location. A record of this duration was found necessary to provide a good value for the average heat flow, in view of the substantial fluctuations which occurred in readings at some positions.

At the mid-point of the test run, temperatures at approximately 50 locations throughout the wall were measured and recorded.

Air velocities over the panel surfaces were adjusted to reduce vertical air temperature gradients to an acceptable minimum. The velocities under these conditions were approximately 500 fpm on the cold side and 250 fpm on the warm side. These air flow conditions were maintained constant throughout all tests.

Description of Wall Tested

The basic wall panel used throughout consisted of 3/8-in. plasterboard, 2- by 4-in. studding spaced 16 in. on centers (actual dimensions 1½- by 3⅝-in.), 25/32- by 10-in. spruce shiplap sheathing, building paper, and 6- by ½-in. bevel cedar siding. The exterior siding and sheathing and interior plasterboard were secured with wood screws rather than nails, and the siding was given one prime coat and two finish coats of white exterior paint to reduce air infiltration. In addition, the joints between framing and exterior finish were sealed with masking tape. All spaces between the panel and the test opening were packed with wood fiber insulation.

A total of eight different wall constructions was studied. Only four different forms of insulation were used, but further variations were introduced in certain details of application. The various panels are listed as follows:

Panel Number	Description of Insulation
1	Uninsulated.
2	Warm side of air space covered with aluminum foil.
3	Single foil curtain creating two equal air spaces each faced one side with aluminum foil. Curtain sealed to all surrounding framing members.
4	1-in. thick glass-fiber board creating two equal air spaces. Sealed to all framing members.
5	2-in. thick mineral wool batt placed next to plasterboard to form one air space on cold side of insulation.
6	Same as 5, except batt placed against sheathing.
7	Same as 3 with 3/8- by 14½-in. gap at top and bottom.
8	Same as 4 with 3/8- by 14½-in. gap at top and bottom.

The 1-in. glass-fiber board insulation installed in walls 4 and 8 was used to simulate a blanket insulation since its dimensions and its location in the wall were more strictly defined.

Test Results

Figs. 3 to 10, inclusive, represent a graphical presentation of the test results. Each of the figures illustrates the vertical temperature variation at different planes throughout the wall, and the corresponding variation of heat flow into the wall. In all figures, the following numbering system has been used to identify the temperature curves.

Curve Number	Location
1	Warm side air 1 in. from wall surface.
2	Inside surface of plasterboard.
3	Outside surface of plasterboard.
4	Air space, ¾ in. from plasterboard.
5	Air space, ¾ in. from sheathing.
6	Inside surface of sheathing.
7	Cold side air 2 in. from wall surface.

It should be noted that the thermocouples in the air space were placed at geometric locations rather than in accordance with air flow lines. For this reason they did not indicate precisely the variation in temperature of the circulating air. It is possible that the temperature gradients shown for these locations illustrate less severe conditions than actually occurred.

The heat flow rates given were obtained from observed heatmeter millivoltages using the conversion data provided by the manufacturer of the instrument, without further calibration.

Heat Flow into Walls with Air Spaces

In all the walls tested in which the interior finish was exposed to an

Fig. 3—Temperature and heat flow variation in Wall No. 1—uninsulated

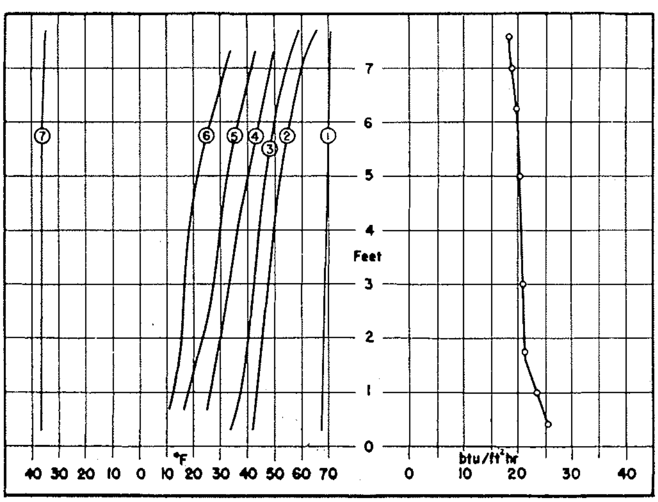
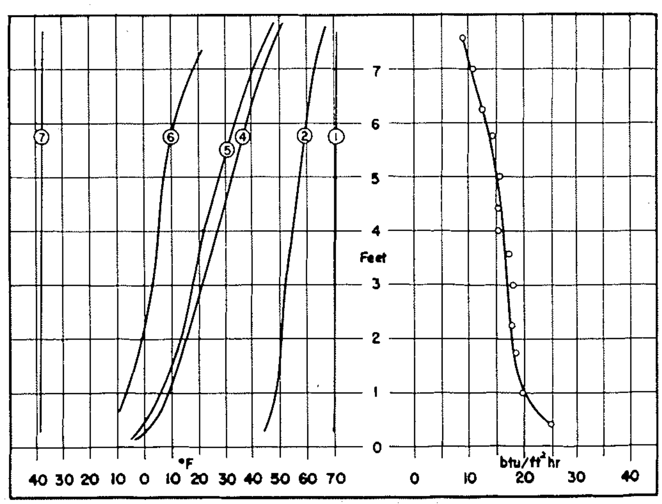


Fig. 4—Temperature and heat flow variation in Wall No. 2—warm side of air space covered with aluminum foil



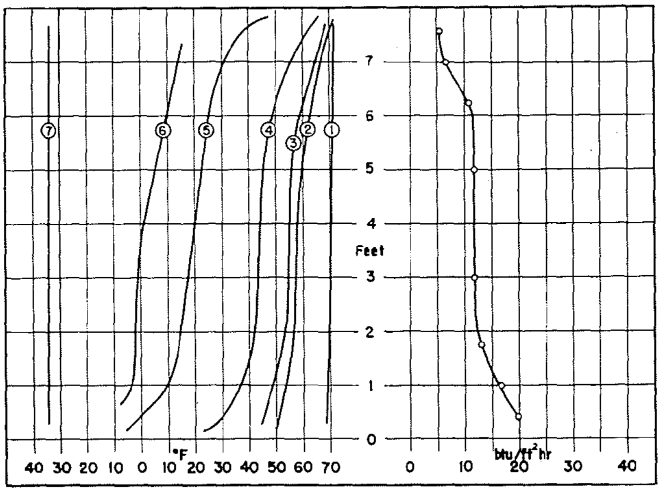


Fig. 5—Temperature and heat flow variation in Wall No. 3—insulated with single foil curtain creating two air spaces. Foil sealed to surrounding framing members

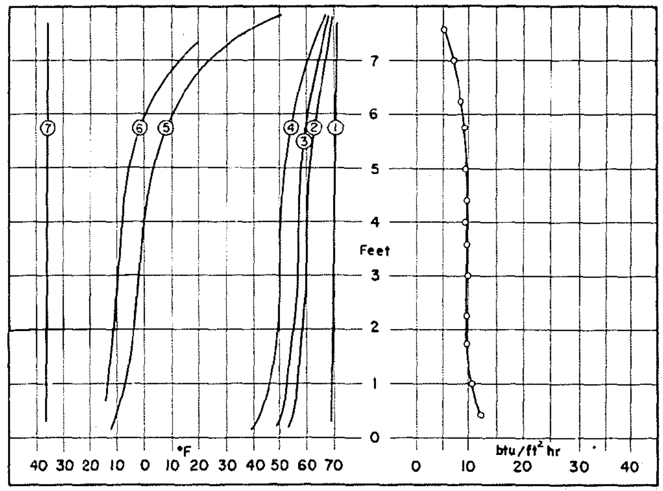


Fig. 6—Temperature and heat flow variation in Wall No. 4—simulated blanket-type insulation. One-inch board, creating two air spaces, sealed to surrounding framing members

air space, the rate of heat flow into the wall decreased with increasing height. This general feature was in keeping with the simple analysis presented previously in the paper. This same variation was exhibited to a lesser degree by Wall No. 5, aside from the increased heat flow rate measured at the 4-ft level. It was found on examination after test, that the sealing strip at the junction of the two 4-ft batt lengths had become detached, and it is likely that some infiltration of air from the outer air space occurred at this discontinuity in the insulation.

Table 1 is presented to facilitate comparison of the various walls as to vertical heat flow variation and overall average values. In preparing this table, the mean rate of heat flow into each wall was calculated from the curves of Figs. 3 to 10 and the heat flow rates at different heights were expressed as percentages of this value. These percentages are shown in the table for the various walls, arranged in order of decreasing magnitude in heat flow variation. It will be noted, however, that the heat flow into the bottom region of Walls No. 6 and 8 was a greater percentage of the average than for Wall No. 3, although the overall variation for these walls was not as extreme. Apparent overall transmittance values were also calculated by dividing the mean heat flow rate by the inside to outside air temperature difference and multiplying by a factor of 1.25 to bring them to closer agreement with accepted values. This factor for heatmeter readings on frame walls has been proposed also by Prof. E. R. Queer in a private communication. It will be noted that the transmittance for the uninsulated frame wall is thus brought very close to the accepted value for such a construction. The transmittances thus found are given in Table 1, together with the corresponding air-to-air temperature differences. Although ambient conditions were not exactly duplicated in all the tests, inside to outside temperature differences were sufficiently close to permit some general comparisons to be made.

Table 1—Percentage Variation in Rate of Heat Flow with Height for Walls with Air Spaces

Wall		Average Heat Flow	Percentage of Average Heat Flow Distance From Bottom of Wall — Inches								Inside — Outside Temperature Difference	Apparent Average Transmittance
Number	Insulation	Btu/ft²hr	6	18	30	42	54	66	78	90	F	Btu/ft²hr F
7	Single Foil Curtain — ⅜-in. gap top and bottom	15.1	229	131	106	90	77	64	53	50	103	0.183
3	Single Foil Curtain — Sealed	12.0	159	117	100	98	98	98	83	46	105	0.143
8	1-in. board — ⅜-in. gap top and bottom	14.5	173	126	107	96	84	77	69	70	98	0.185
6	2-in. batt — next to sheathing	7.9	165	115	106	94	87	83	80	71	102	0.096
2	Reflective surface — warm side of air space	16.2	146	117	110	108	96	91	76	56	108	0.188
4	1-in. board	9.3	130	108	104	105	105	102	89	59	106	0.110
1	Uninsulated	21.1	120	104	101	100	98	96	93	88	103	0.256
5	2-in. batt — next to plasterboard	6.4	109	98	97	103	108	98	97	89	104	0.077

It has been proposed by Prof. F. A. Joy, also in a private communication, that the conversion factors to be applied to heatmeter readings may vary with the resistance of the material between the heatmeter and the first air space encountered in the wall. In view of the doubt which exists on this point it is necessary to consider heatmeter readings carefully, even for comparative purposes, when there has been some change in the arrangement of material on which the heatmeter has been placed. This will apply particularly to the reading obtained for the Wall No. 5 arrangement, in which the mineral wool batt was placed against the back of the plasterboard. The other arrangement which might be questioned is that of Panel No. 2; in all other cases there was a normal air space immediately behind the plasterboard.

The effect of substituting a reflective foil for one of the surfaces bounding an air space in an uninsulated wall resulted in a decrease in the overall heat transferred, but at the same time increased the variation in heat flow from top to bottom. The apparent transmittance at the bottom of the wall, was in fact, increased to a value greater than the average transmittance for the uninsulated wall.

Wall No. 3, representing a wall with a single-foil curtain insulation, exhibited a greater vertical variation in heat flow than all other walls except for Wall No. 7 in which this same insulation was installed with gaps top and bottom. These results, when considered together with the performance of Wall No. 2, suggest that the effects of convection are more pronounced in walls insulated with reflective insulation. This feature is to be expected when it is considered that reflective insulation reduces radiant heat transfer to a minimum so that convective transfer predominates. Walls insulated with such materials will therefore exhibit the characteristics of convective heat transfer to a greater degree.

The effect of gaps at the top and bottom of an intermediate membrane in the air space was to increase the extent of heat flow variation over that for similar walls in which no such openings existed. In the case of the foil curtain insulation, these gaps resulted in an increase of 68 percent in the average heat flow into the wall while for the simulated blanket-type insulation the increase was approximately 30 percent. The average transmittance values for the two walls having improperly sealed insulations were approximately equal, however.

In any consideration of the effects of openings in intermediate membranes in walls, the influence of gaps in exterior or interior coverings is also suggested. It would be expected that openings such as these would have a still greater influence on the thermal characteristics of a wall. For example, in Walls No. 7 and 8, openings at the top and bottom of the exterior sheathing would result in cold outside air being induced into the wall by chimney action and the inside finish would offer the only protection against outside weather. It is not too unlikely that such gaps will exist in some cases since the trend in recent years has been to increase the permeability of outside portions of the wall to reduce the possibility of condensation.

Gaps in interior coverings frequently result in practice from the installation of electrical outlets, and improper sealing around windows and doors. The effects of induced circulation may be even more serious in these cases since the air entering the wall will contain a considerable amount of moisture. These features, although not covered in the experimental work presented, are nevertheless closely associated with convection in walls.

The location of semi-thick batt-type insulation appears to affect both the variation in heat flow with height and the overall average transmittance. From a comparison of the test results for Walls No. 5 and 6, placement of such insulation at the warm side of the air space has advantages from both points of view. The lower average transmittance for Wall No. 5 cannot be readily explained and suggests that more extensive investigation of this phenomenon is required.

Because of the extreme variations in heat flow resulting from convection, transmittance values obtained by application of small heatmeters at single points on a wall may be quite incorrect in the case of walls with air spaces. Full appreciation should be given to these disturbing effects in assessing performance data for hollow walls.

Fig. 7—Temperature and heat flow variation in Wall No. 5—insulated with 2-in. mineral wool batt—air space on cold side of insulation

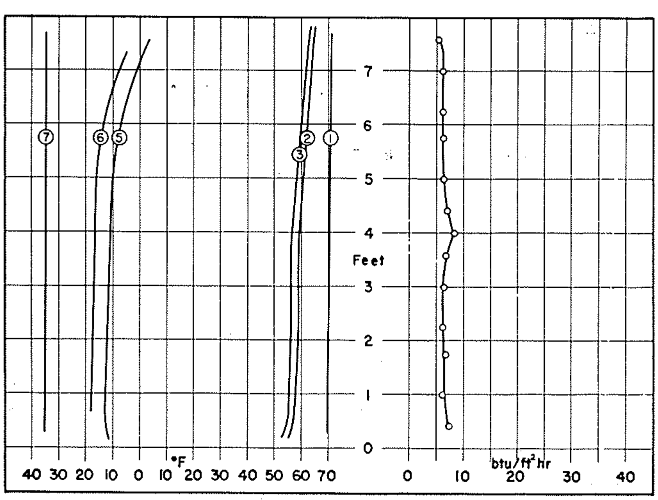
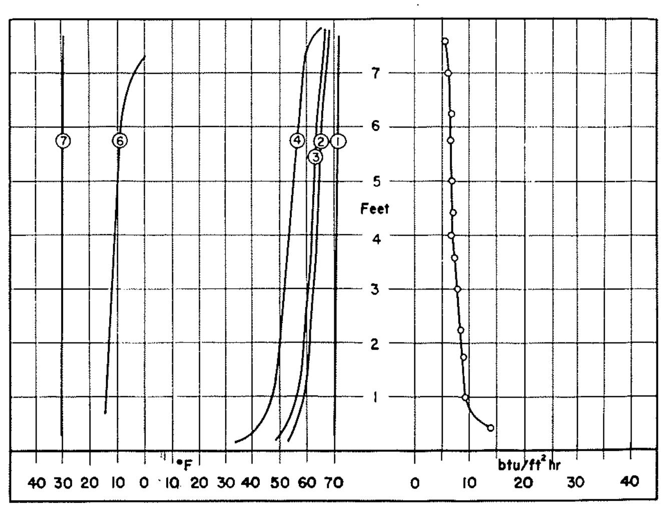


Fig. 8—Temperature and heat flow variation in Wall No. 6—insulated with 2-in. mineral wool batt—air space on warm side of insulation



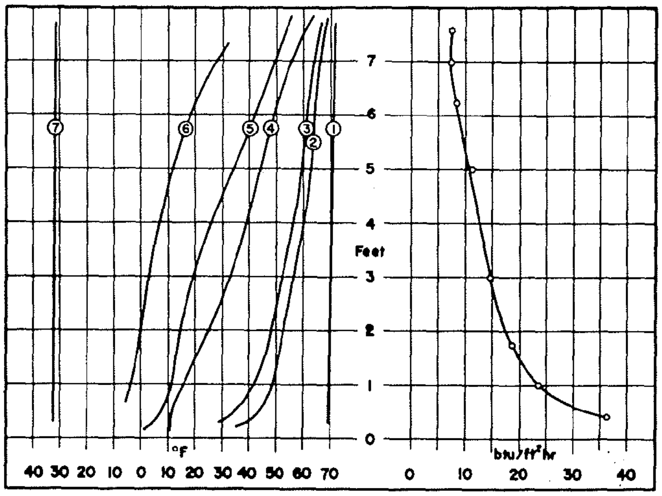


Fig. 9—Temperature and heat flow variation in Wall No. 7—insulated with single foil curtain creating two air spaces—3/8-in. gap top and bottom

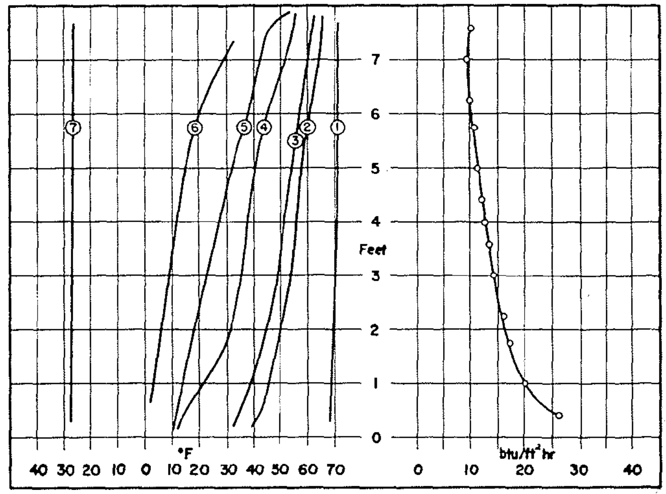


Fig. 10—Temperature and heat flow variation in Wall No. 8—simulated blanket-type insulation—1 in. board creating two air spaces—3/8-in. gap top and bottom

Temperature Distribution in Walls with Air Spaces

The temperature of the inside surfaces of walls is an important feature to be considered in the assessment of wall performance. Such temperatures are closely associated with the problems of surface condensation and dust marking, since both result from a lowering of surface temperature. Usually the temperature of the wall surface is calculated on the basis of simple theory employing the resistance concept. Since this method is based on the assumption of uni-directional heat flow, considerable error results when it is applied to walls with air spaces. Calculation of inside surface temperatures in the usual way, based on a surface film coefficient of 2.7 as given in THE GUIDE* for a velocity of 250 fpm and using the average overall transmittance values from Table 1 provides values in all cases which are higher than those found by test, even for the upper portions of the walls. The variations in temperature drop from air to surface as given by the differences between curves 1 and 2 in Figs. 3 to 10 indicate in a general way the marked deviations in air film conductances with height.

*HEATING, VENTILATING, AIR CONDITIONING GUIDE, published by THE AMERICAN SOCIETY OF HEATING AND VENTILATING ENGINEERS, 62 Worth St., New York 13, N.Y.

In all cases, inside surface temperatures varied a great deal more than would be expected, temperatures over the lower portions of the walls being consistently low. In the case of Wall No. 7, the effect of improper sealing of the foil curtain resulted in a surface temperature of approximately 35 F at the 6-in. level. Under such conditions, condensation on this area would result if humidities on the warm side exceeded 27 percent at 70 F.

Temperatures of the inside surface of the exterior sheathing in the walls studied also departed widely from the uniform conditions usually assumed, as may be noted in Figs. 3 to 10. The temperatures of this surface are closely associated with the problem of condensation within walls and are, therefore, of considerable importance in any analysis of wall performance.

In general, sheathing temperatures varied with height in a similar manner to temperatures of the inside finish and it is obvious that wide discrepancies will exist between actual values and values calculated by simple theory.

Conclusions

From the results obtained in this preliminary study of air spaces in walls it is concluded that:

1. The convective action within air spaces in walls has a much greater influence on the temperature distribution and heat flow pattern than is usually assumed.
2. The variations in heat flow and temperature resulting from convection appear to be more pronounced in walls containing reflective insulation than in similar walls having normal surfaces.
3. Improper sealing of blanket-type insulation, or reflective-curtain insulation, installed so as to create multiple air spaces, may result in an increase in both vertical heat flow variation and in overall transmittance.
4. Presently accepted theory based on the assumption of uni-directional heat flow is entirely inadequate for calculation of temperatures in hollow walls.
5. The use of small heat-flow meters to evaluate the overall transmittance of walls may lead to erroneous results unless a complete vertical traverse is taken.

Acknowledgments

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