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INVESTIGATIONS INTO THE AIR-LEAKAGE AND HEAT-TRANSMISSION CHARACTERISTICS OF WINDOWS

Untersuchungen über die Luft- und Wärmedurchlässigkeit von Fenstern

by

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Investigations into the air-leakage and heat-transmission characteristics of windows

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Of the external structural parts of a building, windows are usually the weakest members from the point of view of thermal insulation. The principal function of windows, to admit daylight, leads inevitably to structures which transmit relatively large quantities of heat, since the principal constituent of the window, the pane of glass, cannot be made as thick as one might wish. The quantity of heat passing through can of course be reduced by the use of several panes placed one behind another with intervening air spaces, but there are strict limits to this procedure, principally for financial reasons. Multiple glazing of three or more ply is scarcely ever used in practice. Since, however, windows have to be opened for the purposes of ventilation, unless the rooms concerned are supplied with fresh air by means of ventilation or air-conditioning plant, the more or less considerable air leakage through the unavoidable gaps around the windows when there is a pressure difference across the gaps leads to the exchange of air, and hence of heat, between the heated room and out of doors.

Knowledge of the air-infiltration and heat transmission characteristics of windows is therefore of essential significance for both indoor climate engineering and the design of heating appliances, and hence for the fuel consumption of rooms and buildings. The German standard DIN 4701 (Rules for the computation of heat requirements for buildings) contains data on the air leakage and heat transmission properties of the standard types of window. It nevertheless seemed desirable to check the values given in DIN 4701 by means of measurements obtained from tests on a fairly large number of windows of varying design, and in particular to attempt to account for the factors governing the air infiltration and heat transmission properties of windows.

These investigations which were carried out on behalf of the Forschungsgemeinschaft Bauen und Wohnen, Stuttgart, form the subject of the following report.

1. Theoretical considerations

1.1 Air leakage. The problem of the passage of air through the gaps and cracks around windows has been dealt with by a number of authors [ref. 1], whose results have been summarized by Cammerer and Hirschbold [ref. 2] and used by them in an attempt to derive generally valid relations.

Reiher, Fraass and Settele [ref. 1] studied the air-leakage through gaps, such as occur with windows, in relation to the gap dimensions (width and length) and the pressure difference across the gap. The hourly air flow L (m^3/h) through a window, when the pressure difference across the window is Δp (kg/m^2; mm water column), can be represented by the following equation:

$$L = a \times l \times \Delta p^{2/3}, \qquad (1)$$

where l (m) is the entire gap perimeter of the window and 'a' a numerical value which takes into account the type of window construction and the quality of workmanship in the execution. This a-value can be used as a measure of the air-leakage of a window. It signifies the quantity of air exchanged hourly per metre gap length when there is a pressure difference of 1 kg/m^2, and it is therefore designated as the gap leakage.

Cammerer and Hirschbold [ref. 2] state that for all types of window construction, assuming the same quality of workmanship, the air-leakage depends extensively on the length of the air path through the gap. This means that the air leakage ought to be invariably less through double windows than through compound windows, and less through each of these than through single-glazed windows. This assumption presupposes essentially similar window designs which may be the case with the majority of wooden windows, but which can scarcely be said to be true of metal-framed windows with their wide variability in gap shape. Finally in the case of windows with elastic sealing, very small amounts of air leakage can be obtained which are practically independent of the gap shape. If allowance is made for the extraordinarily large and decisive influence of the accuracy and quality of workmanship, it is found that a mathematical determination of the air leakage of a window on the basis of window construction is scarcely feasible. The only way to obtain data on the air leakage of windows is to obtain measurements from tests on the largest possible number of windows of varying execution and to determine the most frequent values for air leakage and their range of scatter.

1.2 Heat transmission

The term used to characterize the heat transmission properties of a window is the thermal transmittance k (kcal/m^2 h deg.C), which is defined as the quantity of heat flowing per unit time (h) through unit area (1 m^2) of the window when the difference in temperature between the inside and the outside air is 1°C. The thermal transmittance involves the surface coefficients α_w and α_k on the warm and cold sides of the window respectively. In order to be able to compare windows directly with one another as regards their heat transmission properties, the k-values in each case must be related to the same α-values. In the 1947 edition of DIN 4701 the values assumed for windows were $\alpha_w = 10$ and $\alpha_k = 20$ kcal/m^2 h deg.C. The new edition published in January 1959 gives for α_w the value 7 and for α_k the value 20 kcal/m^2 h deg.C. Accordingly, k-values for windows will be met with which relate to different values of α_w depending on the time when the measurements were made. Fig. 1 shows the relation between the k-values with different values of the surface coefficient α_w. When the k-value is greater than 2 kcal/m^2 h deg.C, the effect of α_w is considerable.

The thermal transmittance of a window is determined, apart from the surface coefficients on both sides, by the thermal conductance of the panes and the frame. By adopting simplifying assumptions, it is possible to perform a rough calculation of the thermal transmittance over the window frames. Ignoring the gap shape, locking devices etc., and regarding these frames as solid, plane slab sections, the k-value of the window is obtained from the total resistance values of the frame and the pane and the proportion of window area occupied by each. In the case of windows with double glazing, allowance must be made for the effect of the width of the space between the panes on the thermal resistance of the air contained in that space [ref. 3]. Fig. 2 shows the thermal resistance $1/\Lambda$ of a vertical air-space bounded on each side by glass as a function of the width of the air-space. The thermal insulation of such an air-space increases with increasing thickness and attains a maximum of something over 0.2 m^2 h deg.C/kcal when the thickness is about 25 mm (effect of heat transfer due to radiation between the panes). At thicknesses in excess of 25 mm the thermal insulation falls slightly owing to the convection heat transfer between the panes which then begins to take effect.

Figs. 3 and 4 contain graphs which, based on the relation in fig. 2, the known conductivity values of wood, glass and metal and the frame thickness in cms, show the thermal transmittance k of windows in relation, first, to the proportion of window area occupied by the frames and, second, in the case of doubly glazed windows, to the width of air-space between the panes. It can be seen from these graphs that for windows with wooden frames the k-value decreases with increasing proportion of the total window area occupied by the frames, the reduction being appreciably more for single than double glazing. For metal-framed windows the exact opposite is true. The metal frame, being the part of the window which transmits more heat, increases its k-value with increase in the proportion of area occupied by it. In the case of single glazing, this increase can in practice be neglected, for the k-value is here determined almost exclusively by the surface coefficients on both sides of the window. With double-glazed metal windows, however, this increase exercises a marked effect on the heat transmission properties of the window.

The effect of the width of air-space between the panes on the k-value of double-glazed windows is very distinct for widths up to about 25 mm (decreasing value with increasing distance). For widths greater than 25 mm no appreciable change in the k-value is to be expected, but then, especially with metal windows, the thermal transmittance is decisively affected by the proportion of window area occupied by the frame.

1.3 Heat loss through windows due to temperature differences and wind

The remarks on the foregoing section related to completely tight windows where no exchange of air through the window can take place. Since, however, windows are usually found to have a more or less appreciable air leakage through gaps, the conduction heat loss Q_T of the window, given by the expression:

$$Q_T = k \times F(t_{Lw} - t_{Lk}), \tag{2}$$

must have added to it the heat loss Q_L due to air leakage. By using equation (1), this quantity Q_L can be written in the form:

$$Q_L = 0.31 \times l \times a \times \Delta p^{2/3} \ (t_{Lw} - t_{Lk}). \tag{3}$$

In equations (2) and (3) F (m^2) denotes the window area, t_{Lw} and t_{Lk} (°C) the air temperatures on the warm and cold sides of the window respectively.

The total heat loss $Q_{tot} = Q_L + Q_T$ through the window can be calculated with the aid of a value k_{tot} which takes into account the air leakage, and hence the heat loss, through the gaps:

$$\begin{aligned} Q_{tot} &= k_{tot}\, F(t_{Lw} - t_{Lk}) \\ &= (k\, F + 0.31\, l\, a\, \Delta p^{2/3})\ (t_{Lw} - t_{Lk}). \end{aligned} \tag{4}$$

By introducing the quantity w for the ratio of gap length l to window area F (DIN 4701, 1959 edition)

$$w = \frac{l}{F}, \tag{5}$$

we obtain

$$k_{tot} = k + 0.31\, w\, a\, \Delta p^{2/3}. \tag{6}$$

This k_{tot}-value is therefore determined by the thermal transmittance k, the gap leakage a and the pressure difference across the window. k_{tot} is shown in fig. 5 as a function of the pressure difference for a window with a k-value equal to 3 kcal/m^2 h deg.C for various a-values. (w is assumed here to have the value 4). It can be seen from this figure that the heat loss through the gaps around windows, when there is a pressure difference at the window due to wind, is primarily governed by the amount of air leakage. Accordingly the conduction heat loss becomes a factor of secondary importance.

2. Test measurements

Laboratory tests were conducted on a large number of different types of window design in order to yield information on their infiltration characteristics, thermal transmittance and condensation on the windows and, in those with double glazing, condensation in the air-space between the panes. These tests were supplemented by others on windows incorporated in a building and thus exposed to the weather. In collating and assessing the results, the measurements obtained from these tests were supplemented by others previously obtained by the author [ref. 4].

2.1 The test windows

The laboratory tests were conducted on windows of the same size (external dimensions 112 cm x 138 cm (3' $8\frac{3}{4}$" x 4' $7\frac{1}{4}$")) made available by the relevant manufacturers. The types of window examined were as follows:

Wooden windows

Pivoted-double sash windows with and without window post, single-glazed as compound and box windows with different widths between the panes as well as with double glazing in one frame;
pivoted sash-compound window;
slide-compound window;

Windows with plastic frames

Pivoted-double sash windows with double glazing in one frame;

Windows with light metal frames

Pivoted-double sash-compound windows;
pivoted-double sash windows with double glazing in one frame with and without elastic sealing;

Windows with sheet steel frames

Pivoted-double sash-compound windows with elastic sealing;
pivoted-double sash windows with single glazing with and without elastic sealing;

Steel windows

Pivoted-double sash windows with single glazing;
turning sash window with single glazing.

A certain percentage of these windows was made available also in larger dimensions (130 cm x 180 cm [4' 4" x 6']; 140 cm x 250 cm [4' 8" x 8' 4"]). These windows were permanently built into the external wall of the experimental construction at the Institute and thus exposed to the weather.

2.2 Determination of gap leakage

The laboratory tests were performed on windows in the state in which they were delivered (wooden windows primed, metal windows partly primed, partly anodised or galvanized [steel windows]), as well as on primed windows to which two coats of paint had been applied. The windows incorporated in the experimental construction were not tested until after final surface treatment.

2.21 Experimental procedure

Those windows not incorporated in the test house were inserted into a box in such a way that they formed a terminating surface of the box. Any remaining gaps between the external frame of the window and the box were carefully sealed. Air was blown into, or extracted from, the box by means of a fan and a flow meter was included to measure the volume of air escaping or infiltrating through the gaps around the window, depending on the overpressure in the box. The windows were so inserted into the box that during test an overpressure existed on the outside of the window. The air temperature and air pressure outside the box were recorded at the same time, thus enabling the measured values of air flow to be converted to the standard conditions (0°C, 760 mm mercury column).

Measurements were taken several times with each window. After each measurement the window was opened and closed again several times. This meant that the results obtained usually differed somewhat from one another, and so the mean value had to be determined for further evaluation. With the entire gap perimeter known for the window concerned, it was then possible to calculate the gap leakage a.

In the case of the windows built into the experimental house, a box was placed in front of the window on the room side and sealed to the wall. The test procedure was the same with this set-up as with that just described. In order with these built-in windows to obtain information on the air leakage between window and wall, the gaps around the sashes were carefully sealed with adhesive strips and the measurement procedure repeated.

2.22 Results

2.221 General findings. The air leakage of the windows was determined generally when the pressure difference across them was between 0.5 and 10 mm water column, but sometimes also when it was greater than 10 mm. The relation between the volume air flow per metre gap length and pressure difference, when plotted on a double logarithmic scale, is found in the majority of cases to be linear. On the whole, the inclination of the lines obtained by plotting the measured values is approximately the same as that to be expected according to equation (1), i.e. the flow conditions in the window gaps obey the same laws (fig. 6). In a few cases the inclination of the lines differed more markedly from that given by equation (1). As already mentioned, some of the windows when opened and closed several times gave air leakage values which differed somewhat from one another. Fig. 6 shows (shaded portion 1) the extreme values obtained with such a window. Curves 3 and 4 show L as a function of Δp for two windows, the frames of which became deformed with increasing pressure difference, thereby enlarging the gaps through which air infiltrates. In one case this deformation occurred when the pressure difference was little more than 2 mm water column, the members of the window frame here being very thin and flexible. The majority of the windows were sufficiently stable and showed no appreciable changes in the gaps even at high pressure differences (up to 50 mm water column) (curve 2 in fig. 6).

2.222 Wooden windows. The wooden windows made available for test, and tested in the state in which they were delivered (primed), were found to have a-values between 0.6 and 1.7 Nm^3/h the commonest value being 1.25 Nm^3/h. No systematic effect of the type of window on the gap leakage could be established with only 15 tested windows.

After two coats of paint were applied to the frames, the air leakage values varied from 0.3 to 1.3 Nm^3/h, the most frequent value being 0.4 Nm^3/h.

These relatively low a-values prompted the supposition that the window specimens submitted had been manufactured with special care. In order to elucidate whether this were the case, the suggestion was made that larger series of windows of the same execution should be tested for air leakage. Thanks to assistance rendered by the Federal Ministry of Housing, it was found possible to obtain measured a-values from investigations which formed part of a larger building project [ref. 4]. The manufacturers of these windows were not informed of the intended investigations until after they were completed so that it could be assumed that the windows tested had the average quality of the windows of the manufacturers concerned. In all, 159 wooden windows by four different manufacturers were tested for gap leakage. The windows were single or double sash compound windows with the external dimensions 140.5 cm x 132 cm (4′ 8″ x 4′ 4¾″), 140.5 cm x 157 cm (4′ 8″ x 5′ 2¾″) and 140.5 cm x 195 cm (4′ 8″ x 6′ 6″). They were tested for gap leakage immediately after manufacture and priming. The a-values then obtained varied between 0.5 and 3 Nm^3/h, the most frequent value being 1.2 Nm^3/h. Fig. 7 (curve 3) shows the frequency distribution of the a-values of these windows. The same figure contains graphs of the frequency distribution of the a-values of the single windows (primed and painted twice) tested in the laboratory. Examination shows that the series windows did indeed yield the same most frequent value of gap leakage as the single windows, but that with the latter the range o scatter of the a-value was decidedly narrower than with the former.

Finally, 40 of the series windows were incorporated in the experimental house and painted and then tested again for gap leakage. The frequency distribution curve obtained then for the a-values is that numbered 4 in fig. 7. These values, of course, take into account the effects of the paint and the gaps between the window frames and the house wall on the gap leakage (volume of air flow relative to the gap length of the window). The range of scatter of the a-values (window gaps and gaps between window and wall) extends from about 1 to 3.5 Nm^3/h per metre gap length. The most frequent value lies somewhat above 2 Nm^3/h.

All the given gap-leakage values apply to practically new windows. In the course of time, however, these values are liable to change as a result of wear and tear due to opening and shutting, weather, rain, sun etc., depending on the type and quality of window. The timber is liable to shrink or expand, elastic sealings may change in their properties and therefore sometimes more or less lose their effectiveness, metal fittings are liable to work loose etc.

Some of the windows built into the experimental house at the Institute were examined for gap leakage immediately after assembly in the wall and again after three years' wear and tear and exposure to the elements. The gap leakage values are shown compiled in table 1.

<u>Table 1</u>. Gap leakage of wooden windows built into the experimental house

Window	built into	gap leakage (Nm^3/h)	
		immediately after assembly in wall	after three years
pivoted-triple sash compound window	south wall	0.3	0.6
pivoted-triple sash compound window	south wall	1.2	1.3
pivoted-triple sash compound window	south wall	0.35	1.0
pivoted-triple sash box window	south wall	1.0	1.1
pivoted-sash compound window	north wall	0.45	0.5

It can be seen from this table that the gap leakage in every case has increased in the course of time, the relative increase being greatest for windows with originally very low a-values.

2.223 Windows with plastic frames

Two windows with plastic frames were made available by the same manufacturer for the present tests, one a pivoted-two sash window with double glazing and elastic gap sealing (dimensions 112 cm x 138 cm [3' $8\frac{3}{4}$" x 4' $7\frac{3}{4}$"]) and the other the same, but with three sashes (140 cm x 250 cm [4' 8" x 8' 4"]). The three-sash window was built into the north wall of the building. The gap leakage test on these windows, tested in the state in which they were delivered, resulted in an a-value of 0.2 Nm^3/h for the two-sash window and one of 0.3 Nm^3/h for the three sash window.

The built-in window showed cracks in the rubber sealing after about one year. The plastic frame became so severely distorted that the window could no longer be shut satisfactorily. After about three years parts of the frame broke off in the vicinity of the handle. Further tests on this window for tightness were therefore futile.

2.224 Metal windows

As regards frame design, metal windows are found to vary much more than wooden ones. The frames which consist of members, some extruded or cast and others rolled, the metals used being steel and light alloys, exhibit a very wide variety of cross-sectional shapes. Window frames made of sheet steel form a special group. Fig. 8 shows some sections through the metal windows tested.

When delivered, the metal windows had already been provided with the necessary surface protection (stoved paint, anodised, galvanized). When these windows were without special sealing, the a-values obtained were between 0.5 and 2.5 Nm^3/h. The highest a-values obtained were 2.6 and 2.4 Nm^3/h for the two steel windows tested (fig. 8e and f). The commonest a-value of these windows as well as of other metal windows (predominantly with light metal and sheet steel frames) tested at the Institut fur Technische Physik was 1.6 Nm^3/h (fig. 9, curve 1).

Metal windows with elastic sealing (fig. 8a, c and d) tested in the state in which they were delivered, had a-values of 0.3 to 0.5 Nm^3/h. One series comprising 32 windows with light metal frames and elastic sealing had a-values between 0.2 and 1.5 Nm^3/h, the most frequent value being 0.6 Nm^3/h (fig. 9, curve 2).

The lowest a-value of 0.1 Nm^3/h was obtained for a window with light metal frame, tested as delivered, in which sealing was effected by specially shaped grooves which fitted tightly into one another when the window was shut.

Windows of this type were also tested for gap leakage in the series tests already mentioned [ref. 4]. The testing of 32 such windows in a building resulted in an a-value (air flow through the gaps around the window including the crack between window and wall, relative to the gap length of the window) between 0.5 and 3 Nm^3/h, the commonest value being 1.5 Nm^3/h. These tests were extended to include a further 26 windows built into the experimental building, the frames being of light metal without special sealing. Their a-values varied from 1.3 to 3.3 Nm^3/h. Curve 3 in fig. 9 represents the frequency distribution of the gap leakage of these two series of window (a total of 58 windows).

Some of the window constructions tested in the laboratory had been built into the Institute's experimental building and they were tested for gap leakage immediately after being built in and again after three years' wear and tear and exposure to the elements. The results obtained are given in table 2.

Table 2. Gap leakage of some metal windows built into the experimental building

Window	built into	gap leakage (Nm^3/h)	
		immediately after assembly in wall	after three years
pivoted-three sash compound window with elastic sealing	south wall	0.5	0.85
pivoted-three sash compound window with elastic sealing	south wall	0.3	0.35
pivoted-three sash compound window without special sealing	south wall	0.75	0.9

2.3 Thermal transmittance. The thermal transmittance k was determined for windows measuring 112 cm x 138 cm (3′ 8¾″ x 4′ 7¾″) after final surface treatment (wooden windows given two coats of paint; metal windows painted, anodised or galvanized).

2.31 Experimental procedure. The window for test was fitted with no gaps into an opening in a partition separating a cold and a warm room, so that the inside of the window faced into the warm room. During the period of test the air temperature in the warm room was kept at 20°C and that in the cold room at 0°C. The warm side of the window was fitted with a box about 35 cm deep which contained built-in electric heating to keep the air at the same temperature as that of the warm room surrounding the box (i.e. at 20°C). Fans were used to circulate the air in each of the two rooms and in the box so that no appreciable differences occurred in the air temperature in the vicinity of the window surfaces or around the box. The air temperatures were recorded by means of thermocouples arranged in groups of twelve on each side of the window and in the warm room.

During test the heat energy supplied to the box by the electric heating unit flowed exclusively through the window, the air temperature being assumed the same in the box and in the warm room. Let t_{Lw} be the air temperature on the warm side of the window and t_{Lk} (in deg.C) that on the cold side, F (m^2) the window area and Q (kcal/h) the quantity of heat which flows per hour in the steady state through the window and is measured electrically. The thermal transmittance k_M can then be obtained from the following equation:

$$k_M = \frac{Q}{F\ (t_{Lw} - t_{Lk})}. \qquad (7)$$

The k_M-value thus determined holds true only for the particular values of the surface coefficient α_{wM} and α_{kM} on the warm and cold sides of the window respectively. In order to convert the measured thermal transmittance values to the standard values of the surface coefficient $\alpha_{wN} = 7$ and $\alpha_{kN} = 20$ kcal/m^2 h deg.C, it is essential to know the α-values during test. These can be calculated from the air temperatures t_{Lw} and t_{Lk}, the mean surface temperatures $\bar{t}_{ow}$ and $\bar{t}_{ok}$ and the quantity of heat Q according to the following equations:

$$\alpha_{wM} = \frac{Q}{F\ (t_{Lw} - \bar{t}_{ow})}, \qquad (8)$$

$$\alpha_{kM} = \frac{Q}{F\ (\bar{t}_{ok} - t_{Lk})}. \tag{9}$$

The mean surface temperatures $\bar{t}_{ow}$ and $\bar{t}_{ok}$ on the window are obtained from the equations:

$$\bar{t}_{ow} = \frac{F_G \times t_{Gw} + F_R \times t_{Rw}}{F}, \tag{10}$$

$$\bar{t}_{ok} = \frac{F_G \times t_{Gk} + F_R \times t_{Rk}}{F}, \tag{11}$$

where t_{Rw} and t_{Rk} = the surface temperatures (measured by means of thermocouples) on the window frame,

t_{Gw} and t_{Gk} = the surface temperatures on the glass surfaces,

F_R = the area of the frame,

F_G = the area of glass,

F = the total window area.

Combining equations (7) to (11), we finally obtain the desired k_N-value for the surface coefficients α_{wN} and α_{kN} as:

$$k_N = \frac{1}{1/\alpha_{wN} + \frac{F_G\ (t_{Gw} - t_{Gk}) + F_R\ (t_{Rw} - t_{Rk})}{Q} + 1/\alpha_{kN}} \tag{12}$$

The procedure for recording temperatures calls for great care, especially when the windows have single glazing, since in this case the temperature differences between the two surfaces of the pane are very small. One method which has proved excellent for producing correct results is to solder the thermal-couples to thin copper foil and to stick the soldered joints very carefully to the panes. The heating wire used should be not more than 0.2 mm in diameter.

An attempt should be made by means of suitable air circulation to keep the surface coefficients at the window as close as possible during test to the standard values. This is particularly necessary for the warm side and with single-glazed windows, since in this case the effect of the surface coefficient on the k-value is specially pronounced.

2.32 Results. Table 3 gives the measured k_N-values converted to the standard values of the surface coefficients ($\alpha_{wN} = 7$, $\alpha_{kN} = 20$ kcal/m^2 h deg.C) for the various types of window.

Table 3. Thermal transmittance values of the windows investigated.

Window type	k (kcal/m² h deg.C)
Wooden windows:	
pivoted sash window, single glazing, (2 sash)	4.35
pivoted sash compound window (2 sash)	1.95 to 2.2
pivoted sash box compound window (2 sash)	2.1
balanced sash compound window	2.1
slide compound window	1.9
Windows with plastic frames:	
pivoted sash window with double glazing, (2 sash)	2.8
Windows with light metal frames:	
pivoted sash window, single glazing, (one sash)	5.0
pivoted sash compound window (2 sash)	3.25 to 3.7
pivoted sash compound window (1 sash)	2.9 to 3.15
pivoted sash window with double glazing (1 and 2 sash)	3.0 to 3.15
balanced sash compound window	3.2
Windows with sheet steel frames:	
pivoted sash window, single glazing, (1 sash)	4.9 to 5.0
pivoted sash window, double glazing, (1 sash)	2.8
pivoted sash compound window (2 sash)	3.1
Steel windows:	
pivoted sash window, single glazing, (2 sash)	5.1
turning sash window, single glazing	5.05

This table shows that windows with wooden frames and double glazing (windows with fixed double glazing or compound windows) differ only a little from one another in their thermal transmittance values. Greater differences in the k-value were found with double-glazed metal windows.

It is found from theoretical considerations on the heat transmission properties of windows that the proportion of window area occupied by the frame and, in the case of double glazing, the width of the air-space between the panes are factors of decisive importance for the k-value of the window. In order to check how far this is true of the window types used here (the calculation was carried out for greatly simplified window frames), graphs were drawn showing the k-values obtained for the windows as a function of the proportion of window area occupied by the frame (fig. 10) and as a function, in the case of wooden windows, of the width of air-space between panes (fig. 11).

It can be seen from fig. 10 that for wooden windows the calculated values show very good agreement with the measured values. Since with double-glazed wooden windows the width of air-space was usually 20 mm and more, i.e. values which do not lead to appreciably different thermal resistances of the air cushion, the calculation for 20 mm width of air-space is practically correct for all wooden windows.

Fig. 11, which shows the k-value of wooden windows as a function of the width of air-space, also has plotted on it the point showing the k-value obtained for a width of air-space of 6 mm. The agreement between calculation and measurement is satisfactory.

With double-glazed metal windows, the relation between k-value and proportion of area occupied by the frame is admittedly seen also to be largely as expected in theory, but the scatters are here much wider than with wooden windows. The reason for this is to be found in the wide variation in the design and shape of the members comprising the frame. Thus, windows with sheet steel frames have relatively low k-values owing to the small thickness of metal (about 1 mm), whereas those with light metal members (see fig. 8a and b) with their greater thickness give somewhat less favourable k-values. The window with the highest k-value of 3.7 kcal/m^2 h deg.C had a relatively thick metal profile and its width of air-space was only 12 mm, two reasons for the high thermal transmittance. transmittance.

Excellent agreement is found between the measured and calculated k-values of single-glazed metal windows. Even with these windows, the values obtained with sheet steel frames are somewhat more favourable than those with solid steel frames.

2.4 Condensation with windows

The chief consideration as regards thermal insulation in the design of the external structural parts of buildings (walls, roofs etc.) is the avoidance of condensation on their internal surfaces. In the case of multi-leaf structures care is also necessary to ensure that no inadmissible condensation forms within them. These problems apply also to windows. Their thermal insulation is usually poorer than that of walls etc., and so the surface temperature on the room side of the window can, depending on the outdoor temperature, lie below the dew point of the room air, while that on the room side of the walls remains above it. Condensation then forms on the windows, but not on the walls.

With double-glazed windows there exists the possibility of condensation forming on the inside surface of the external pane, if water vapour is able to penetrate from the room into the air-space between the panes and cannot escape completely, or at least to an adequate extent, into the open air.

2.41 Surface condensation

The lower the thermal transmittance of a structural part separating a warm from a cold room, the closer will the internal surface temperature of that partition be to the temperature of the room air. In windows, the panes and frames, i.e. parts having different k-values, are adjacent to one another. Consequently, the surface temperatures which become established on the room side of windows in heated rooms will be different. Table 4 gives typical k-values for panes and frames.

Table 4. k-values of glass panes and frames of windows

	k(kcal/m^2 h deg.C)
Single glazing	5.1
Double glazing with 20 mm wide air-space ...	2.5
Wooden frame	1.45
Metal frame	about 5.25

Fig. 12 shows at a glance the surface temperature on the warm side of windows as a function of the outdoor temperature when the temperature of the room air is 20°C. It can be seen that relatively low surface temperatures are to be expected particularly on single panes and on metal frames at low outdoor temperatures. Consequently, on these parts of windows the precipitation of condensate, and at very low outdoor temperatures the formation of ice, must be expected at lower humidity values in the room than would be the case with wooden frames and double glazing. The graph in fig. 13 shows for a room-air temperature of 20°C the relation between the outdoor temperature and the relative humidity in the room, such that, if for any point on any curve the actual outdoor temperature falls below that indicated by the point or the relative humidity exceeds that indicated, condensation will result. Thus, at 40% relative humidity and 20°C room temperature, wooden frames and the panes of double glazing remain free of condensation until the outdoor temperature falls to about -20°C, whereas panes of single glazing and metal frames will show condensation at outdoor temperatures of about 0°C and below. This applies particularly to solid metal frames or to those in which the heat flow path continues without interruption through the metal members from outside to inside.

These considerations do not apply to those cases where a heating unit is placed underneath the window, since the rising warm air causes the temperature in the vicinity of the window to be higher than was assumed in the calculation, and the heat transfer from the air to the window to be greater than that on which the calculation was based. Experience shows that the use of a heating unit below a window enables condensation on the latter to be extensively avoided down to low outdoor temperatures.

Figs. 14 a and 14b show ice formations on wooden and metal windows with double glazing observed when the outdoor temperature was about -15°C. It should, of course, be noted in this case that the rooms into the external wall of which the windows were incorporated, were only moderately heated during the observation period, and the walls and floors still retained a considerable amount of the moisture consumed during their construction, so that the conditions obtaining were decidedly less favourable than would normally be expected in a thoroughly dried out building. It is precisely for these reasons, however, that these pictures show the characteristic differences of the windows with particular clarity.

2.42 Condensation in the air-space with double glazing. Windows with two panes one behind the other are designed and executed as compound windows, double windows or double-glazed single windows. In the case of the 'compound' window, one pane is inserted into the principal sash, the other into the cleaning sash. The double window is in principle two single windows which are either inserted completely separately into the wall or are built into a box-like frame joining the two windows. In the case of double-glazed single windows, two panes are glazed in one frame. They can be securely connected to one another at the edge, so that they are inserted like a single pane or built in one after another with the insertion of a spacer.

During the cold season a vapour pressure difference is present across the window (e.g. warm side: air temperature 20°C, rel. humidity 50%, partial pressure of the water vapour 8.75 mm mercury column; cold side: 0°C, 60%, 3.6 mm mercury column; pressure difference 5.15 mm m.c.). This vapour pressure difference causes vapour to diffuse into the air-space between the panes, unless this space is sealed off and rendered vapour proof. This occurs, however, only where the two panes of the double glazing are fused or soldered together along the edges or are stuck together at the edge by means of some impervious compound. Compound and double windows, on the other hand, usually have around them gaps which connect the air-space between the panes with the warm room and through which vapour can permeate to a greater or less extent. Since, however, the internal surface temperature of the pane on the cold side sometimes falls below the dew point of the moist air then present in the air-space, condensation will occur on this surface. This phenomenon is a frequent source of complaint with compound and double windows, and it can be observed even in those windows where the two panes are glazed in one frame if the putty or sealing compound used does not remain impervious to moisture or if gaps or cracks form between pane and putty or putty and frame. Finally, in such windows with wooden frames there also exists the possibility of water vapour diffusing through the wood into the air-space.

In so far as complete sealing off of the air-space between the panes from the warm room is impossible, and with compound and double windows of the designs in common use this is scarcely feasible or only so with difficulty, the phenomenon described can be suppressed by providing small openings between the air-space and out of doors. These openings merely have to enable the water vapour which has penetrated into the air-space to diffuse into the open air. They can therefore be of a sufficient size (a few cm^2) to permit this, without reducing the thermal insulation of the air cushion. These openings require to be filled with a finely porous filter material, such as mineral wool, in order to prevent the penetration of dirt and vermin into the air-space. The diffusion resistance of such filters can be kept sufficiently low in order to achieve the intended result, without appreciably impairing the thermal insulation of the window. The following, though somewhat exaggerated, "recipe" can be given for avoiding condensation between the panes: "have the sealing as tight as possible on the warm side, but as leaky as possible on the cold side".

3. Summary

The theoretical and experimental studies on wooden and metal windows of varying design have resulted in the following:

Air leakage. The air leakage of windows without special sealing depends to such a large extent on the accuracy and quality of workmanship in making them that characteristic differences between single, compound and double windows practically do not exist. No differences could be found on the average between wooden and metal windows when they were new. In view of the fact that the air leakage of built-in windows increases the more they are used, and that the incorporation of the windows in the building usually gives rise to additional gaps between wall and window, the mean air leakage of windows without special sealing may be assumed to be 3 Nm^3/h per metre gap length and 1 mm water column pressure difference, within the meaning of table 4a in the German standard DIN 4701. Windows with special sealing, as specified in DIN 4701 "Windows with guaranteed sealing", have low air-leakage values with a much narrower range of scatter than windows without special sealing. The value of 1.2 - 2 Nm^3/h, given in DIN 4701 for "windows with guaranteed sealing" is assumed to be somewhat high. A value of not more than 1 Nm^3/h seems reasonable.

Thermal transmission. The values given in DIN 4701 for the thermal transmittance k of single-glazed wooden and metal windows, 4.5 and 5.0 $kcal/m^2$ h deg.C respectively, were fully confirmed by the present investigations.

As for both wooden and metal windows with double glazing (fixed double panes, compound and double windows), the width of air-space and the proportion of window area occupied by the frame are the two principal factors which determine their thermal transmittance.

For wooden windows of all types (except those with single glazing) with the average proportion of window area occupied by the frame varying from 35 to 40% and width of air-space greater than 20 mm, the k-value ranges from 2 to 2.2 $kcal/m^2$ h deg.C. When the proportion of area occupied by the frame is 30%, k increases to 2.3 $kcal/m^2$ h deg.C, and when it is 50%, k falls to 1.9 to 2.0 $kcal/m^2$ h deg.C.

Metal windows, depending on the type and execution of the frames, show a somewhat wider range of k-values than wooden windows. With metal windows also the proportion of area occupied by the frame is a factor of major importance as regards heat transmission, the k-value increasing with increasing proportion of area, the reverse to wooden windows. The effect of the type of metal window, whether compound or fixed panes, on heat loss is of minor importance compared to that of the proportion of area occupied by the frame and that of the frame construction, whether of solid metal or sheet steel. The average k-value of metal windows with double glazing varies between 3 and 3.5 $kcal/m^2$ h deg.C.

References

1. Raisch, E.: The air leakage of building materials and structural components. Ges-Ing. 1928 51, 481.

Raisch, E.: The heat transmission and air leakage characteristics of windows of varying design. Ibid 1922, 45, 99.

Eberle, Ch.: Tests on the air leakage and heat loss of windows. Ibid 1928 51, 566.

Sigwart, K.: Air leakage of wooden and steel windows. Ibid 1932, 55, 515.

Reiher, H., Fraass, K., and Settele, E.: The problem of the air leakage and heat transmission of windows. Wärmewirtsch. Nachr. 1933, 42 and 55.

Settele, E.: The problem of the air leakage and heat transmission of windows. Ibid 1933, 7, 111.

2. Cammerer, J.S. and Hirschbold, F.X.: Influence of window design on the air flow through cracks. Ges-Ing. 1938, 61 (29), 393-9.

3. Mull, W. and Reiher, H.: The thermal insulation of air spaces, its experimental and graphical determination. Beihefte zum Ges.-Ing., Series I, issue 28.

Krings, A. and Olink, J.Th.: Heat transfer through double and multiple glazing with tightly sealed-in gas space. Glastechn. Berichte 1957, 30, 175.

4. Schüle, W.: Air leakage of windows. Ges.-Ing. 1961, 82, 181.

5. Hermann, E.: Light metal window frames in the light of recent German patent rights. Aluminium 1955, 31, 505-508, 561-564 and 624.

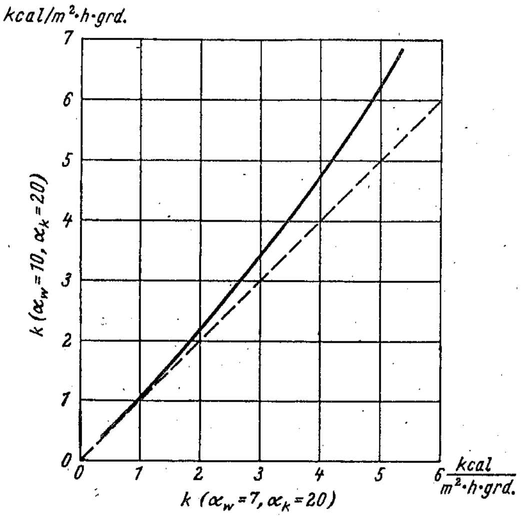

Fig.1. Graph showing the relation between the k-values of a window, if these values hold true for a surface coefficient α_w on the warm side of 10 kcal/m^2 h deg.C (ordinates) or 7 kcal/m^2 h deg.C (abscissal). Surface coefficient α_k on the cold side: 20 kcal/ m^2 h deg.C.

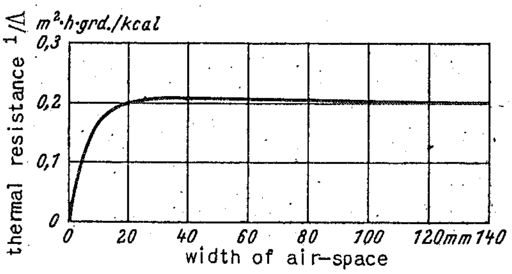

Fig.2. Thermal resistance $^1/\Lambda$ of a vertical air-space bounded on each side by glass as a function of its width (mean temperature of the air-space 5°C).

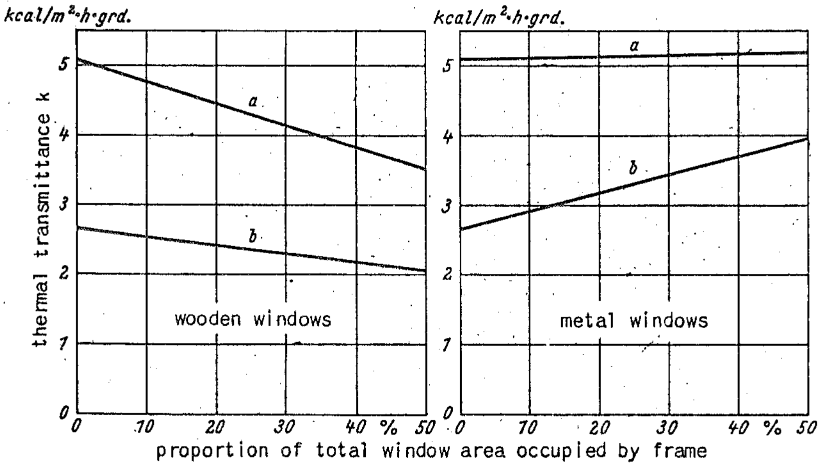

Fig.3. The thermal transmittance k of single-glazed and double-glazed windows calculated in relation to the proportion of the total window area occupied by the frame.

a: single-glazed windows,

b: double-glazed windows (width of air-space 20 mm).

α_w = 7 kcal/m^2 h deg.C,

α_k = 20 kcal/m^2 h deg.C.

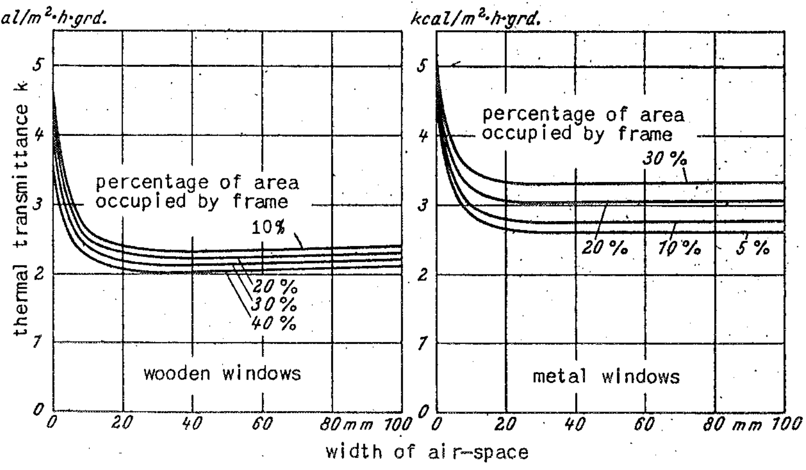

Fig.4. Thermal transmittance k of double-glazed windows as a function of the width of air-space for different percentages of total window area occupied by the frame.

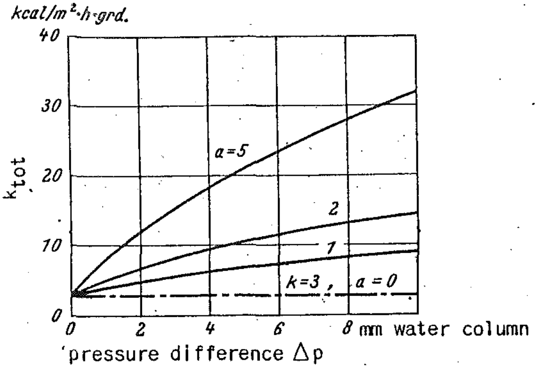

Fig.5. Thermal transmittance k_{tot} of a window ($k = 3$ kcal/m^2 h deg.C) taking into account air leakage (gap leakage $a = 1.2$ and 5 Nm^3/h), as a function of the pressure difference Δp across the window.

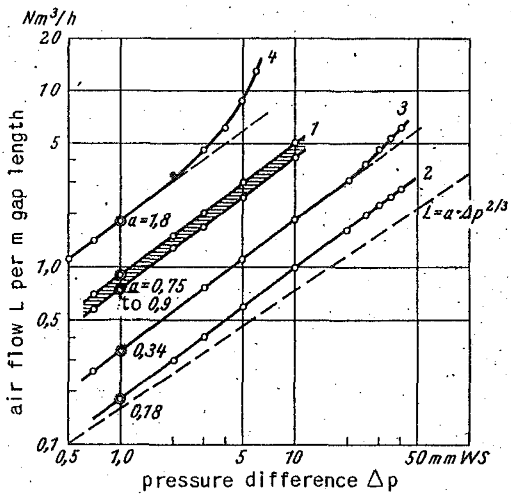

Fig.6. Air flow through various windows per metre gap length as a function of the pressure difference across the window.

1. Range of scatter of air-flow values of a window after it has been opened and shut several times.
2. Windows with extensively constant gap width.
3. Window gaps become enlarged when pressure difference exceeds 20 mm w.c.
4. Window gaps become enlarged when pressure difference is merely above 2 mm w.c.

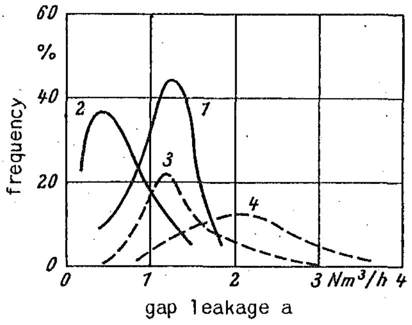

Fig.7. Frequency distribution of the gap-leakage a-values of wooden windows.

1. Window primed; single windows made by different manufacturers and delivered for test.
2. Window primed and given two coats of paint; single windows made by different manufacturers and delivered for test.
3. Window primed; series windows made by 4 different manufacturers, total of 159 windows.
4. Window primed and given two coats of paint; 40 windows of series 3, built into house (air flow at 1 mm w.c. through the gaps around the windows including the gaps between window and wall, in relation to the gap length of the windows).

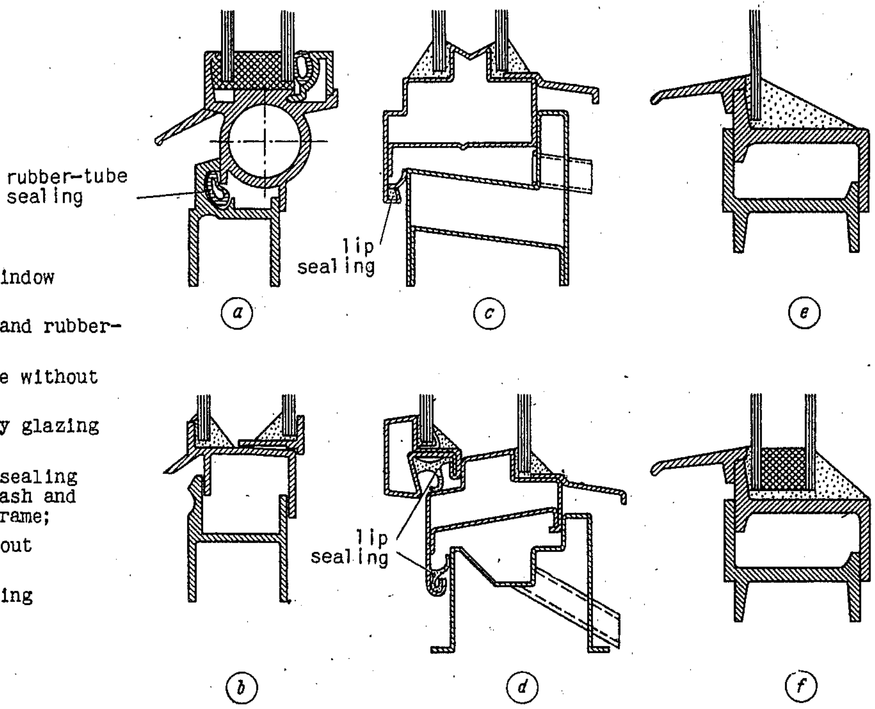

Fig.8. Vertical sections through metal window frames.

a) double window with light metal frame and rubber-tube sealing;

b) compound window with light metal frame without special sealing;

c) sheet steel window with fixed-in 2 ply glazing and lip sealing;

d) sheet steel compound window with lip sealing between cleaning sash and principal sash and between the latter and the external frame;

e) steel window with single glazing without special sealing;

f) steel window with fixed-in 2 ply glazing without special sealing.

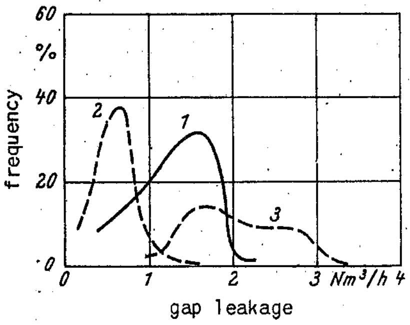

Fig.9. Frequency distribution of gap leakage a of metal windows.

1. Single window without special sealing made by different manufacturers and delivered for test.
2. Series windows made by 2 manufacturers (32 windows); windows with elastic sealing;
3. Series windows made by 2 manufacturers built into house (air flow at 1 mm w.c. through the gaps around the windows and assembly frame and between the latter and the wall, in relation to the gap length of the windows).

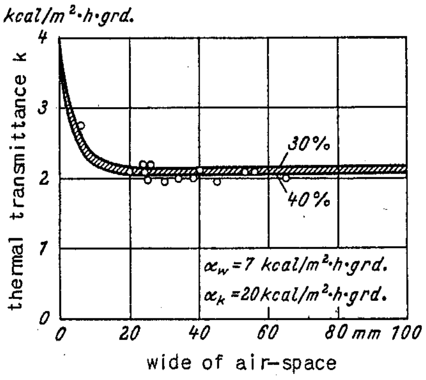

Fig.11. Thermal transmittance k of the tested, double-glazed wooden windows as a function of the width of air-space.

Shaded area: calculated for windows with 30 and 40% window area occupied by frame.

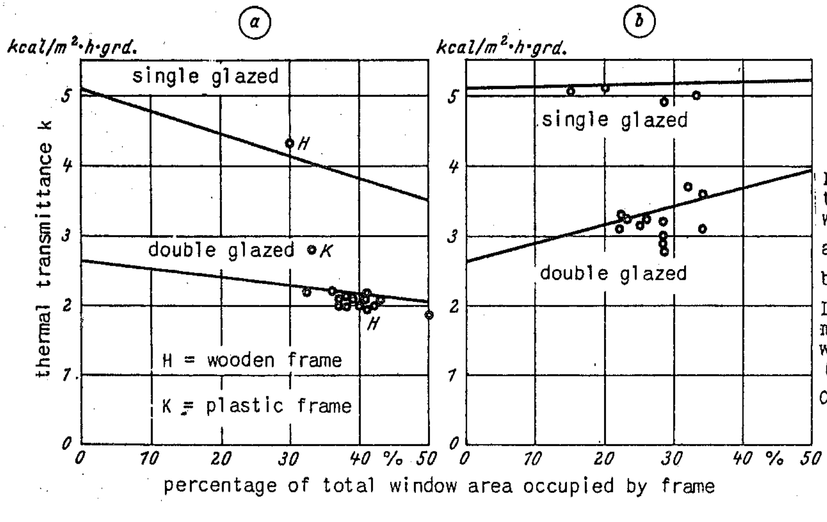

Fig.10. Thermal transmittance k of the windows tested, as a function of the proportion of total window area occupied by the frame.

a) windows with wooden or plastic frames,

b) metal windows.

Lines drawn in: calculated for wooden or metal windows. With double-glazed windows the width of air-space is 20 mm
(α_W = 7 kcal/m^2 h deg.C,
α_k = 20 kcal/m^2 h deg.C.).

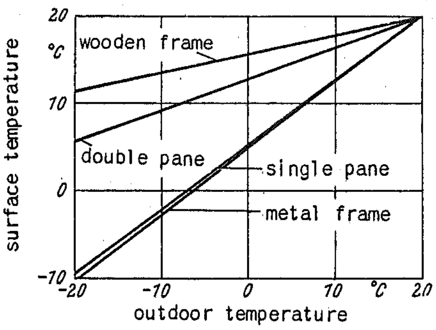

Fig. 12. Surface temperatures on the room side of windows in relation to the outdoor temperature when the room air temperature is 20°C.

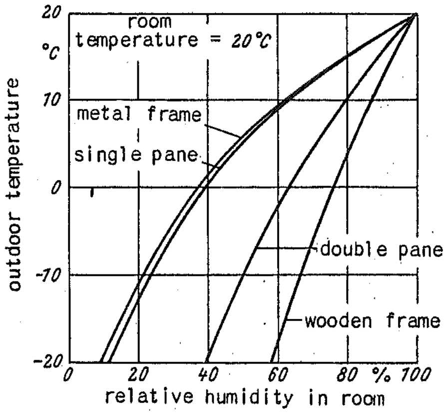

Fig. 13. Outdoor temperatures below which condensation on windows is to be expected, in relation to the relative humidity of the room air at 20°C.

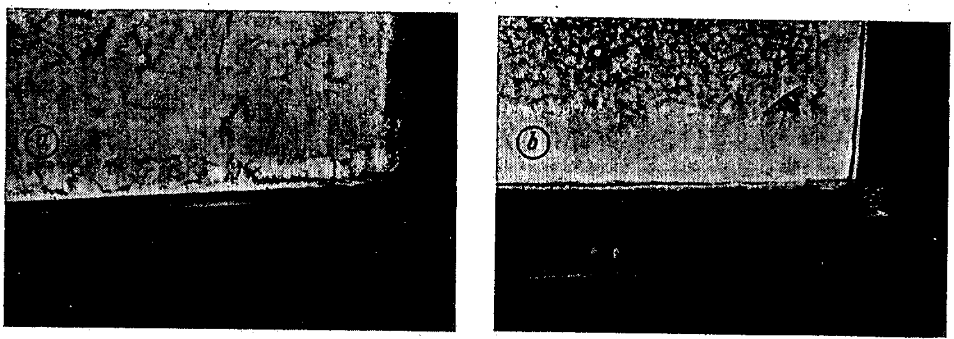

Fig. 14. Ice formation on windows.

a) wooden window with double glazing,

b) metal window with double glazing.

Outdoor temperature -15°C.