

The window in context: The influence of the other components of a building on the function of the window

A progress report (31.12.2001) on Tim Padfield's contribution to Energistyrelsens 'Projekt Vindue'

A full report, with diagrams and references, will be ready for the next meeting 7-8 February 2002.

Summary

The usefulness of windows as ventilators depends strongly on the general construction of the house. This article concentrates on the materials of walls and roof. The main thesis is that the use of porous, water absorbent walls, without an airtight barrier, allows windows to be used as the primary ventilation method, in spite of their postulated disadvantages: draughts and inability to recycle heat. This is because the ability of absorbent walls to store and transmit heat and moisture and to absorb pollutants means that windows can be opened at times when they will cause the least discomfort and loss of energy.

1. Ventilation: the logic behind the rules

The present standards for ventilation in houses in northern latitudes, half an air change per hour and five litres of fresh air per person per minute [refs to standards], are designed to minimise the damage done by three characteristics of the indoor environment: emission of water vapour by people, emission of carbon dioxide by people and emission of more or less poisonous and smelly chemicals from both people and from the house and its furnishing. These bad influences can be removed, or much reduced, by other means than dragging fresh air in through ventilators at a constant, legally fixed rate. The higher molecular weight (VOC) pollutants can be absorbed into porous walls and carbon dioxide and water can diffuse right through porous walls. In addition, large quantities of water can be reversibly stored in the surface few millimetres of porous, absorbent walls and ceilings. These largely ignored aspects of building materials would, if exploited, allow intermittent ventilation through windows at times when the inconvenience and energy loss would be minimal.

The conclusion is that windows with a finely adjustable range of opening, from a narrow gap to opening of the complete area, will work particularly well with absorbent porous walls of low pollutant emission. In this way we can move the emphasis in building physics from the trend towards the intelligent building, full of sensors, actuators and ducts, towards the development of materials that can moderate the indoor climate by non-mechanical means.

2. The economic argument

Modern houses, even their windows, are so well insulated that energy lost as heat in the ventilated air is a considerable portion of the total cost of keeping warm in the winter [ref]. There is therefore pressure to install heat exchangers, which in turn require mechanical ventilation through well defined ducts, to prevent air bypassing the heat exchanger. The house must therefore be made airtight, which has proved to be surprisingly difficult. The window is thus reduced to a source of light, inconstant but still the cheapest light source in energy cost, and a source of radiant energy, which may or may not be desirable, depending on the time of year and other aspects of the design and use of the building. One must mention that glass walls are sometimes ventilated, to allow convective flushing of hot air from the building's

periphery and thus screen the interior from the intense solar gain of an entirely glass facade. The entirely glass clad building cannot take advantage of the material properties described in this article and is not discussed further, except in the section on condensation damage resulting from air flow through the structure.

3. The separation of functions

This tendency to separate the functions of ventilation and natural lighting is an example of a general movement in the development of materials, and in the choice of materials, where one divides a building into its functions and then develops components to serve just one purpose. One sees this tendency particularly in thermal insulation, where the thermal resistance is the number one judges performance by, apart from price, of course. There are, however, load bearing semi-insulators such as cellular concrete. There are moisture stabilising insulators, such as recycled paper and hemp. And there are impermeable insulators such as glass foam. These combinations of properties are not used to best effect in modern building. So it is with windows, where the two abilities of the window, to ventilate as well as to illuminate, are not fully balanced in our present way of designing buildings.

The traditional window is a troublesome component. The high thermal transmission has been largely cured by modern technology, which is abundantly treated in other contributions to this project. The poor durability of the sealing and the generally high maintenance need have not really been solved, particularly for windows that are openable. The impermeability of the window glass ensures condensation under even transitory temperatures below the indoor dew point. The necessary smoothness of the surface ensures that the condensation slides off and concentrates in puddles that threaten rot in the wooden parts and mould on the metal and plastic parts.

This is why it is necessary to study the window in the context of the whole building, so that qualities in the other components compensate for the deficiencies of the window, or even turn these deficiencies into virtues.

This contribution to ‘The window project’ is therefore devoted to almost everything other than the window, in order to give a wider perspective to the debate.

4. The consequences of recent developments in window technology

To summarise the arguments discussed above: the issues that are raised by the recent developments in window and building technology are these:

It is easier to make sealed windows with very high thermal resistance, so ventilation is more logically achieved by other means, leaving transmission of daylight and scenery the only essential qualities of the window.

The high thermal resistance of all modern building components makes the loss of heat through ventilation, deliberate or not, a relatively large consumer of energy. This puts pressure on architects to install airtight windows, because openable windows become a source of unregulated ventilation as the sealing deteriorates or the structure warps.

The larger glass surfaces made possible by the good thermal properties make larger impermeable surfaces. This does not alter the behaviour of modern buildings so much,

because all other surfaces are impermeable. There is, however, accumulating evidence that permeable walls have beneficial effects on the indoor climate, in a way that should force a re-evaluation of the role of the window in ventilation.

This article treats these matters from the point of view of building physics, taking no account of the fact that most of today's buildings, good and bad, will form the basis of our housing stock for a century to come and many new windows will be installed in existing buildings.

5. Cleaning the indoor air

The cleaning up of the urban air over the last forty years has made it possible to clean the inside air by ventilation alone. Ventilation typically uses 30% of the total energy used to keep the occupants comfortable in a well insulated house. The incentive to curb energy use is counterbalanced by the desire to provide the ideal indoor climate, where ventilation is used to remove the products of human metabolism – mainly water vapour and carbon dioxide, but also other, smellier chemicals.

The first thing to note is that ventilation is not the only way to remove these chemicals: one could also use active surfaces that absorb, or transmit these gases to the outside. In modern buildings we do the exact opposite: making interior surfaces which are both impermeable and which themselves contribute to the load of unwanted airborne chemicals. There is a vast literature on indoor air pollution and some legislation to limit outgassing of particularly poisonous species such as formaldehyde. The emphasis, however, is largely 'analytical-regulatory': setting limits for acceptable pollution rather than encouraging the development and use of fundamentally non-polluting materials. To take one example, non-outgassing silicate bound paint has been available for over a hundred years but is hardly used indoors and to only a limited extent outdoors.

One other relevant point about indoor pollution is that the occupants are more tolerant of pollutants if the temperature and relative humidity are moderate. The optimum ventilation rate for comfort is therefore dependent on other factors than the rate of generation of pollutants from people and from furnishings and from the structure of the house.

6. Maintaining a comfortable temperature

Constancy appeals to engineers; they like to have things under control. There is, however, some evidence that people do not dislike varying temperature, which is another supposed defect of natural ventilation, but adapt to it. [Brager, G.S. and De Dear, R., 2000 A standard of natural ventilation, ASHRAE Journal, 42(10), 21 – 27.]

7. The problem of relative humidity (RH)

Hitherto, high relative humidity indoors has been regarded more as a threat to the structure of the house than as an irritant to the occupants. The argument is that a high indoor relative humidity, combined with an indoor temperature above the outside temperature, will result in a dew point for the inside air that is higher than the temperature at some point within the wall, towards the outside surface of the house. Water will condense there and cause corrosion and give encouragement to rot inducing organisms to germinate and thereafter flourish. The better the insulation the lower the temperature at the outside surface of the house. Modern insulation technology has therefore exacerbated the threat of condensation. One must also note that the

complexity of modern detailing in high technology buildings makes airtightness very difficult to attain [box with examples of condensation damage in building envelopes: Ottawa National Gallery of Art, Smithsonian Arts and Industries Museum]

There is a body of research on indoor air quality, reviewed by Sundell [] which suggests that there is no correlation between people's sense of indoor air quality and the RH. Our bodies have no direct sensor for RH: we guess its value through how moist our skin feels and from the sight of water stains on the wallpaper. There is, however, evidence that our health is worse under both high and low RH.

Low indoor relative humidity is certainly desirable for the health of the building but it is regarded as a threat to the health of the inhabitants, though not so much a threat as high indoor humidity. It has long been known that airborne organisms show minimum viability at moderate RH. At low RH they form a desiccation resistant resting phase, at high RH they grow in comfort. A RH around 50% seems the best compromise, according to a much reproduced diagram. [Simonsen p23]

Ventilation in winter will tend to lower the RH to 20% or less, if the outside temperature is below zero. A higher RH can be obtained in two ways. One way is to restrict the ventilation to allow the build up of moisture from people. Another way, not yet commonplace knowledge among building physicists, is to allow diffusion of water through the wall from the outside. The conventional wisdom is that the driving force for water movement through porous building envelopes is the difference in partial pressure of water vapour outside and in. In cold weather the vapour pressure difference will tend to drive moisture out through the wall. But if the wall is absorbent the moisture content of the material at the outside of the building will be higher because the outside relative humidity in winter is often close to 100%, even in clear weather. When we refer to the dry air of a cold winter day with bright sunlight we are expressing a subjective impression, or our knowledge that the vapour pressure, that is the water vapour concentration, must be low.

The absorbent material towards the inside of the house will have a low moisture content, even though the actual water vapour concentration is higher. This is because the water content of materials is almost independent of temperature, depending mainly on the relative humidity.

Water will therefore diffuse inwards in a wall with a fairly dense absorbent structure, as is given by, for example, tightly packed paper insulation, or wood shaving insulation. The magnitude of this effect is not easily calculated, or measured, and the evaluation of the significance of this mechanism is the subject of current research.

An entirely separate property of absorbent materials is that they can store moisture absorbed from the house interior and release it again later to the interior. The capacity of even the surface few millimetres of an absorbent interior finish is large compared with the capacity of the room air for moisture. This property of materials is nowadays entirely suppressed by the use of paint which is impermeable to the daily cycle of humidity which is characteristic of the modern family house and the lifestyle of its inhabitants.

To summarise these rather complicated arguments: we have good reason to believe that a moisture storing material within the house could moderate the drying effect of winter ventilation through a window and therefore make unnecessary drawing the ventilation air through a mechanical humidifier.

8. The consequences of these environmental considerations for window design

The main theme of this article is that a house made of absorbent, vapour transmitting walls will work together with ventilating windows to provide a pleasant indoor climate without mechanical devices other than a stay to adjust the window opening.

It would clearly be a good idea to moderate the indoor RH for the benefit of both the house and its occupants. If the house is entirely made of glass, the only way is through ventilation, sometimes with humidification and sometimes with mechanical dehumidification. If the house is basically porous, with glass limited to enough area to give light, then the ventilation can be reduced. If the porous house also has a storage capacity for moisture the ventilation can also be quite erratic. A bedroom, for example, could have the window closed at night but opened during the day to 'air' the room. A quaintly old fashioned idea that maybe still has some sense to it. A modernist would doubtless introduce a variation on this idea: a noisy mechanical ventilator could be switched off at night to give peace to the sleepers but activated during the day.

The idea promoted in this article is that it is sensible to combine walls that actively transmit and store moisture with windows that can be opened to ventilate the room when it is not in use, thus removing one objection to the window as ventilator: that it causes draughts and is difficult to regulate. The ideal is to develop walls that are not only non-emitting but which contribute positively to the sense of well-being of the occupants and provide good thermal properties as well.

This is not a utopian dream, it is actually even more difficult to realise than that: there are two powerful resistive forces: snobbery and the desire to impress with technological innovation. It has always been so. In eighteenth century Scotland we read: "As there is no stone in the neighbourhood, the buildings are mostly built of clay, and huddled together without much order or regularity. Excepting Gentlemen's seats, all the old buildings in the parish are of that substance, which, when properly cemented, is reckoned the warmest and most durable of any." [Earth Structures and Construction in Scotland, Historic Scotland, Technical Advice Note 6, p 48]

Nevertheless, there is a group of scientists and ecological activists who are investigating, in both practical and theoretical ways, the advantages of materials such as clay and wood, which are not highly regarded by the modern building industry. Fortunately, both sides regard glass as a good thing, and modern developments in glass technology are undoubtedly of great benefit to the alternative, as well as the orthodox building trade.

A highly instrumented demonstration house in clay has yet to be built, but there is an example of a wooden house, whose properties I will summarise. [Carey Simonsen, Moisture, thermal and ventilation performance of Tapanila ecological house, Technical research centre of Finland, Research Notes 2069, 2001]. Simonsen and co-workers have made a thorough study of the metabolism of this house in Helsinki: its consumption of energy and its balance of humidity and polluting gases. One purpose of their research was to demonstrate the virtues of walls that are permeable to gases right through but they also considered other aspects of porosity mentioned above: moisture and heat storage. They make the assumption that diffusion of any gas through the wall can be deduced from the measured permeability to water vapour of the material, adjusted for molecular weight. The measurements showed that the

apparent ventilation rate was 140% of the rate for the inert, impermeable room (all surfaces covered with polyethylene sheet) when the ventilation rate was 0.8 air changes per hour. This demonstrates some active participation of the wall in allowing diffusive ventilation. Simonsen notes [p 42] that SF₆, a heavy molecule, does not so readily diffuse through the wall, and suggests that porous walls will therefore have a limiting effect on VOC concentrations. His general conclusion is that diffusion of CO₂ through porous walls is measurable but is only significant when the air change rate is about 0.1 air changes per hour: much smaller than the present standard.

One should however note that the SF₆ results apply to relatively unreactive gases, that are not irreversibly absorbed by materials. There is evidence that pollutant gases are strongly absorbed on porous materials, so the improvement in indoor air quality may be quite large. Brimblecombe [Brimblecombe 2001] has shown very strong absorption of nitrite ion, generated from the reaction of nitrogen dioxide with water indoors. Earlier work by * [] showed the strong absorption of sulphur dioxide on woollen furnishing and on wallpaper. Evidence is accumulating that absorbent walls could confer very large benefits in indoor air quality.

One of the most striking results of Simonsen's measurements is the amelioration of the relative humidity in the bedroom containing his sleepers, here represented by an electric humidifier and assorted electronic heat producers. The low air change rate and the good insulation ensured a temperature too high for real sleepers to enjoy: 27C. The significant result, however, is that the rise in RH during the night was the same for the impermeable room with 0.5 air changes per hour and the porous room with 0.1 air changes per hour. There is no doubt that porous walls allow a significant moderating of the daily cycle of water production in bedrooms, bathrooms and kitchens.

The water vapour absorbed into the wall must escape either into the room during periods when it is well ventilated and free of water generating occupants or activities, or it must diffuse right through the wall to the outside. In this second case there is a risk that water vapour will condense within the wall and cause fungal and bacterial growth. Simonsen's team put electrical conductivity sensors into the timber structural members of the house wall and roof. They showed that if the outer surface was about three to five times as permeable to water vapour as the inside surface, the water content of the structural timbers would not reach risky levels. Here again, absorbent materials have unexpected good qualities. Peukhuri et al [2001] show that absorbent insulation, in this case hemp, is very resistant to condensation because at high RH it apparently causes backward movement of water vapour into the house, as described in an earlier paragraph [see figure]. There is much evidence from experience [Schaube on Canadian buildings] that organic insulation lasts well and is not particularly susceptible to organic growth.

There is one final comment concerning the Helsinki house: it was not particularly absorbent! The wall construction was an inner layer of painted plasterboard, then 250 mm of wood fibre insulation, low density wood fibre board, an air gap, then timber cladding. The paint covered gypsum would have a very poor performance as a moisture storage material. The paint was thin and contributed minimally to the diffusion resistance but gypsum, at moderate RH is almost inert to moisture, with very little absorption indeed. It is quite permeable, so the wood fibres beyond were certainly contributing something to the observed moisture storage, but a house designed precisely to give good moisture storage would certainly perform better. The designation 'ecological house' refers mainly to the heavy use of recyclable or compostable

materials and the effort to minimise use of fossil fuel and electrical energy. For this reason Simonsen found little influence on the inside temperature from the latent heat of sorption of water into the materials (see the next section).

I have written much about this house because the quantitative data from this research is the best available. The house uses materials that are abundant in Finland. In Denmark such an ecological house would be better built with Danish raw materials: clay, sand and straw! It would be good if we could make such a thorough investigation of this more appropriate construction. It should provide better moisture storage, according to theory [Padfield 1998,1999].

9. Evaporative cooling and condensation heating

There is another aspect of moisture sorption on porous materials that is relevant to the design and use of windows. The condensation and evaporation of water releases or absorbs heat, which modifies the indoor climate considerably. The direction of the temperature change is not always in the desirable direction! In summer, for example, ventilation can bring in warm humid air, which will be absorbed by the walls, giving more heat to the room. In winter dry air will evaporate moisture from the walls and cool the room further. The most useful role of absorbent walls is during periods of high solar gain without ventilation. The sun-warmed air will fall in RH and will thus evaporate water from the wall. This effect will be even more marked if the wall itself is exposed to direct sunlight. It will lose water vapour to the very warm air at its surface. This is paradoxically a form of heat storage, because when the sun dips below the horizon the cooling wall will re-absorb water from the high relative humidity of the cooling air and give off heat to moderate the approaching cool of the evening.

In this way, porous walls and glass windows are linked in their effect on the indoor climate.

10. Microbiology

The danger of mould growth as a result of moisture diffusion from the inside of the house must be taken seriously. There is much advice given on the subject. The apparently safety first approach often used by architects is to specify an air barrier close to the interior wall surface, in a cold climate. Paradoxically, this may not be the safest solution in the real world. The argument goes like this: Air barriers are never perfect, there are always cracks and defects which channel the air from the interior. The wall materials adjacent to these channels are where condensation will occur first, and it will be abundant, because of the locally high air flow. If the flow is high enough it will of course warm the wall above the dew point, but this is not a hope one can build much trust on.

If, however, the inside air is less humid, because of the buffering effect of the absorbent materials close to the interior surface of the wall, and the furnishing of the house, then the air leaking through towards the outside will have a lower dew point and will be less prone to condensation. This argument is a subtle one, which means that some measurements could help the debate.

There is danger even without condensation. Mould growth is certain if the RH is 100%, and the temperature is above about zero degrees, but there is a risk of growth at lower than saturation RH. There is much data on the limiting RH for biological growth, some of them are unfortunately rendered less persuasive by the lack of care in controlling the RH and by the

failure to distinguish water available in the culture medium from water, at the same activity, in the air. There is also some uncertainty about the effect of ventilation rate over the organism. Nevertheless one can agree that the limit for germination is seldom less than 80% RH [Nielsen 2001, **] and the limit for growth of established organisms is down around 50% RH [Wahrscheid 2000]. These drought resistant organisms are fungi – most bacteria give up at a much higher RH, although some salt dependent bacteria actually need a moderately low RH.

The problem with these numbers is that the ordinary outdoor RH in Denmark is often close to 100% and is seldom less than 50%, so why does mould growth in buildings give us such trouble? There is some vital information missing that must be found before we can rationally design mould resistant buildings.

The current limits for biological growth are quite contradictory when one researches the susceptibility of individual materials – cotton has limits of 95%, or 80% according to two papers []. Many researchers have used culture gels and have thus bypassed the very relevant question of whether water activity alone is the deciding variable. It seems unlikely. We know that dust mites, for example, extract water from the air by exuding a very concentrated solution of potassium chloride onto a part of their skin where they can suck in the more dilute aqueous solution which forms as the initially saturated potassium chloride solution absorbs water from unsaturated air, at about 70% RH. The mite does not directly absorb water vapour from the air, although its activity is defined to be the same: the RH is simply 100 times the thermodynamic potential known as the water activity. There are several ways that organisms gather water in environments that lack liquid water. Some achieve osmotic equilibrium with air at a moderate RH by concentrating salts and soluble organic substances such as sugars in their cell fluid. Other organisms use active, energy consuming methods for pumping water through their skins.

One must suppose that there is a difference in the potency in causing germination of water in a concentrated aqueous solution compared with water as a relatively dilute vapour in air [Franks 1982], even when the water has identical activity in both forms.

Even building materials which should not contain hygroscopic salts or compounds can support mould growth. Sometimes the hygroscopic material is bacterial slime, probably originating in a single episode of wetness.

Another factor influencing the critical RH for growth is the nutrient quality of the substrate. Bacteria can grow on almost anything and the accumulating slime from their metabolism can then give nutrients to the more specialised fungi. We learn to our surprise that nutrients are present even in factory fresh building materials: Brimblecome [2001] reports the presence of nitrite ion in plaster board that cannot have come from atmospheric contamination after manufacture, because nitrite is absorbed so strongly at the surface that it would never reach the interior, where it was detected. Nitrite is a vital nutrient for nitrite reducing bacteria [Krumbein 1989].

The intertwined factors of time-of-wetness and air velocity undoubtedly play an important part in mould infestation. Nielsen[2001] reports a defect in the incubation chamber that he used. Some of his culture dishes had a higher air flow on one side. Here, the colonies were smaller. This is a rare example in the literature where one can confidently rely on other parameters: temperature and relative humidity, being identical on both sides of the culture

dish. Most of the literature on the effects of ventilation on mould growth do not exclude the side effect of high air flow causing a more even temperature and therefore a more uniform relative humidity. The much quoted advice to ventilate to prevent mould growth is a catastrophic short circuiting of the interpretation of the real cause of trouble, which is uneven temperature in the dwelling, with consequent condensation in the coldest places of water released in warm places. This distillation process is the main cause of condensation and mould growth in buildings in cold climates and the advice to ventilate just encourages neglect of the underlying problem.

One must conclude, from this brief summary of the literature on biology and building, that we do not really understand the ecology of biological growth well enough to give well grounded advice on the correct ventilation rate. The abundance of mould growth in the worst ventilated places, typically roof structures, suggests that there are two neglected factors: time of wetness and the uneven distribution of wetness.

This last factor needs to be explained further. The picture [frost under roof tiles in a church] shows frost accumulated under the roof tiles of a church in Sjælland during a period of radiative cooling to a clear sky. The water source is certainly the relatively warmer wooden beams in the roof structure. When the ice melts it will drip from every tile end, giving a pattern of points of wetness on the ceiling below. In this case the water will redistribute itself through the capillaries of the lime mortar on the vault and re-evaporate quite quickly from the relatively warm and porous plaster.

If, however, the ceiling had been insulated with mineral fibre, the water would have drained through onto a plastic vapour barrier where it would form pools, according to the random contours of the plastic sheet. The fibres above would vastly reduce air movement, so the pools would dry out very slowly. During this time moulds could germinate in the 100% RH, which all authorities agree is almost a necessity for starting mould growth on fresh, nutrient poor materials. After a period of growth the organic slime would provide a substrate for growth at a lower RH.

This dramatic scenario is not much to the taste of building physicists, because the formation of pools in, and their evaporation from, irregularly draped plastic is not easily amenable to mathematical modelling. Building physicists would rather model regular diffusion processes which probably account for only a thousandth part of the water movement in real buildings.

My conclusion from this study of the biology of buildings is that we cannot use present knowledge to give confident advice on ventilation, or on building techniques, and must fall back on the experimental background: that well ventilated structures seldom suffer from biological growth to an extent that damages health.

11. Other consequences of condensation

According to Hukka and Viitanan [1999] mould growth stops at zero degrees, even at 100% RH. This does not mean that winter condensation is unimportant. Condensation as ice allows the accumulation of large amounts of water in places where liquid water would rapidly drain away. When the thaw comes, the water can find its way into quite unexpected places [box with stories about the Hirshhorn museum and Renwick Gallery]. The threat from ice comes not only from direct expansion damage.

Simonsen plays down this aspect in his study of the Helsinki house, being satisfied that the water content of the structural timbers is only in the risk area for organic growth during very cold periods. He agrees, however, that the rate of drying as warmer weather comes is very important. Fortunately this seems to be very rapid, given an open construction. Simonsen's data can be supplemented by measurements in two buildings from Washington, which has a surprisingly cold, though short winter [Padfield: Renwick and Arts and Industries]. Measurements from flat roofs, even those with ventilation openings, shows a more mixed picture of drying rate [several articles from conf series Building envelopes in cold climates].

Anyway, it is obviously sensible to reduce the amount of condensation, even if the weather is cold. One should also note that the evaporation rate is low in cold weather, because the carrying capacity of the air stream for water vapour is very low. Even a moderate accumulation rate is dangerous in the cold.

Finally, one should note that the temperature can intermittently rise above zero even in very cold climates, as a result of solar radiation. There is then a possibility of intense distillative movement of water vapour. Hughes [1996] reports dramatic deterioration of the relics in Captain Scott's Antarctic hut, which is usually buried under snow but occasionally subjected to radiant warming of the black tar paper roof.

12. Conclusion

Some important matters emerge from this brief literature survey. Humans thrive best at about 50% RH and 20C. Buildings in a cold climate are put under severe stress by this indoor climate, because of the inevitability of condensation within the structure. Curiously, these are the same conditions that have long been advocated by museum environmental advisors, and have caused much damage to museum buildings, mostly modern ones. This is why a museum curator has offered to make this critical literature survey! My conclusion is that the only way to reconcile the needs of people and of buildings is to look much more carefully at the merits of the porous, absorbent building. Such buildings were once universal but are now rare, and almost all are quite old. In our rush to develop new methods of industrially efficient building we have neglected the study of the subtler merits of old materials and design features. The window particularly has been modernised to high thermal efficiency without much regard to its relationship to the rest of the building and its diverse functions.

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