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IEA Annex 14: The Zolder Case Study

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Abstract

The Zolder case was one of the six case studies on mould problems and surface condensation, initiated within the International Energy Agency (IEA) Annex 14 on "Condensation and Energy". This project, a joint research effort of Belgium, the Federal Republic of Germany, Italy, the Netherlands and the United Kingdom, was completed in March 1990.

Complex relations between mould, surface condensation, energy conservation and parameters such as the outdoor climate, the thermal quality of the building, the ventilation and the occupants' behaviour are explained, followed by an analysis of the Zolder-Lindeman case. This illustrates the extent to which mould may deteriorate the livability of a social housing estate. On three houses, different mitigation measures were evaluated before and after implementation: loft space insulation, inside insulation, double glazing, outside insulation, natural ventilation, and demand controlled ventilation.

The results for one of the three show that the severe mould problems resulted from the combination of poor overall insulation quality and the impossibility of ventilating properly. A thermal retrofit, together with the installation of a natural ventilation system, proved to be successful.

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Introduction

The IEA-Annex 14 work on mould, surface condensation and energy, generated from a widespread feeling in the five countries involved (all countries with a cool to cold, fairly humid winterly climate in part of their territory) that energy conservation measures during the 1970s and early 1980s had increased the number of moderate to severe mould cases. It was feared that this could jeopardize further energy conservation policy. Furthermore, the spread of the problem in low income housing was judged to be no longer socially acceptable.

A Theoretical Approach to Mould and Surface Condensation

Conditions for Mould Growth and Surface Condensation

Mould growth can develop when the mean water activity on a surface remains higher than a threshold value a_w, this being a function of the mould species, the temperature, the moisture situation, and the substrate. In steady state, when the water activity equals the relative humidity, this condition can be written as:

$$p \geq a_w \cdot p_s' \ (a_w \leq 1) \tag{1}$$

with p the (partial) vapour pressure of the air against the surface and p_s' the (water vapour) saturation pressure on the surface. In subsequent text, "partial" and "water vapour" are omitted. Vapour pressure must be read as "partial vapour pressure" and saturation pressure as "water vapour saturation pressure".

Surface condensation starts each time the relative humidity (RH) on the surface reaches 100%, i.e., each time the vapour pressure p equals or becomes higher then the saturation pressure p'_s.

$$p \geq p_s' \qquad (2)$$

The Saturation Vapour p_s'on a Surface

The saturation pressure p_s' at a point on a surface is defined unequivocally by the local surface temperature Θ_s, given by:

$$\Theta_s = \Theta_e + \tau_{hi} \cdot (\Theta_i - \Theta_e) \qquad (3)$$

with τ_{hi} the local temperature factor, Θ_i the inside reference temperature and Θ_e the outside <sol-air> reference temperature. The h_i-subscript for τ emphasizes that the envelope property is coupled to the correct value of the local surface film coefficient. This is important when using thermal bridge calculations to prove or disprove a problem case.

For an airtight flat wall in steady-state thermal conditions (= mean thermal situation), τ_{hi} becomes a surface property, given by:

$$\tau_{hi} = \frac{h_i \cdot R'}{(h_i \cdot R' + 1)} \qquad (4)$$

with R' the "outside-inner surface" – thermal resistance of the wall ($m^2.K/W$) and h_i the inside surface film coefficient ($W/(m^2.K)$). For 2D- or 3D- airtight envelope parts in steady-state conditions, τ_{hi} is a linear or point property, dependent on the geometry of the part, the material combination and the inside and outside surface film coefficients (h_i, h_e).

The local temperature factor is affected by the airflows in leaky envelope parts. If, in wintertime, outside air passes through a part, a local cooling of the inside surface results, lowering the τ_{hi}- values.

In nonsteady-state thermal conditions, τ_{hi} becomes time-dependent, as shown in Figure 1.

Calculating the temperature factor means: solving the thermal balance of a building on the level of each thermal zone (= heating + solar gains + free gains + enthalpy flow + convective exchanges) and each envelope part (= 1D-, 2D- or 3D conduction and air leakage), with a coupling between zone and parts by the convection-radiation-conduction-balance at the inner surfaces.

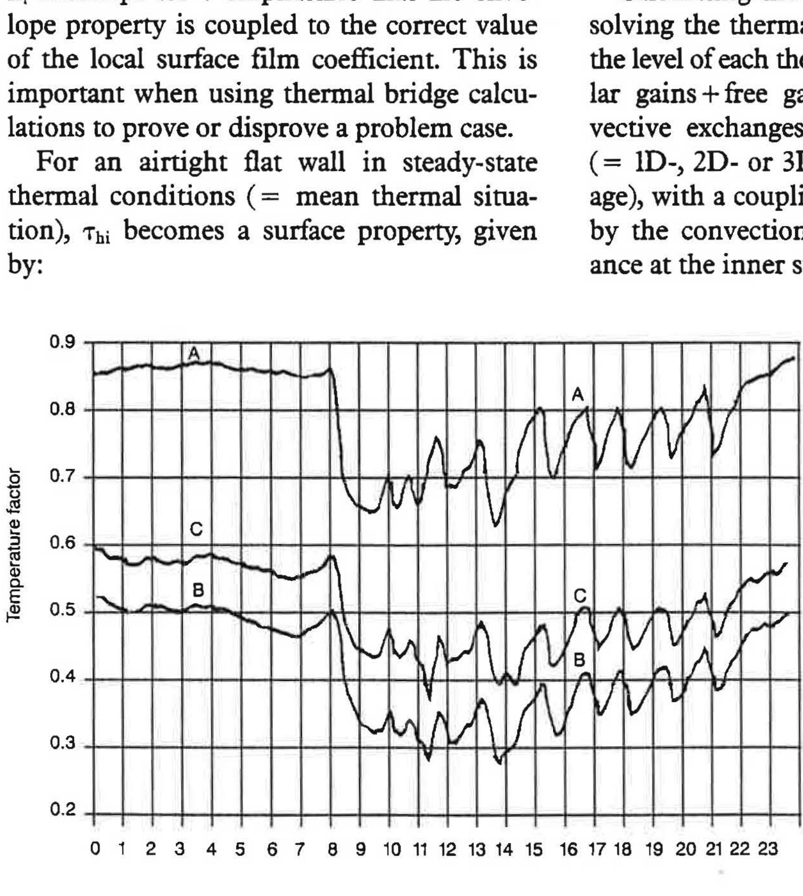


Fig. 1 The temperature factor of the outside wall of the Zolder dwelling living room in non-steady state.

A. Middle of the wall
B. Behind a cupboard
C. In the upper outside corner.

The Vapour Pressure p on a Surface

The different vapour pressures p_{li} on the surfaces l in a building zone i follow from the combination of the zonal hygric balance with the balances at each surface l. If one assumes ideal mixing of the zonal air, the zonal balance becomes:

$$\Sigma(G_{aji}\cdot p_j/RT_i)-p_i\cdot(\Sigma G_{aij})/RT_i + \Sigma\beta_{ki}\cdot A_{ki}(p'_{ki}-p_i)+\Sigma\beta_{li}\cdot A_{li}\cdot(p_{li}-p_i)+G_{pi} = V_i\cdot dp_i/dt \quad (5)$$

with G_{aji} being the airflow from the adjacent zone j to the zone i (kg/s), p_j the vapour pressure in zone j (j = e for the outside), G_{aij} the airflow from zone i to zone j (kg/s), p_i the vapour pressure in zone i, A_{ki} the surfaces in zone i on which condensation or drying of condensate take place (m²), p'_{ki} the saturation pressure on these surfaces, A_{li} the surfaces in zone i (m²), p_{li} the vapour pressure against these (hygroscopic) surfaces, β_{ki} and β_{li} the vapour surface film coefficient at the surfaces A_{ki} and A_{li} (s/m), G_{pi} the vapour production in zone i (kg/s) and V_i the zonal air volume (m³). R is the gas constant of vapour (462 J/(kgK)) and T_i the zonal temperature in K. Σ means that the terms concerned must include all adjacent zones, all condensation surfaces and all hygroscopic surfaces.

V_i. dp_i/dt stands for the air inertia.

The surface balances state that the vapour flow at the airside must equal the flow at the materialside of the envelope part.

This system of balances can only be solved and the values p_{li} calculated if the airflows and the air and all surface temperatures are known. The airflows follow from an interzonal air exchange calculation, and the temperatures from the zonal and surface thermal balance.

If one assumes long-lasting mean conditions (1 month for example), then the hygroscopic influences and the air inertia vanish, the surface balances are omitted and the zonal hygric balance reduces to:

$$\Sigma(G_{aji}\cdot p_j/RT_i)-p_i\cdot(\Sigma G_{aij})/RT_i + \Sigma\beta_{ki}\cdot A_{ki}\cdot(p'_{ki}-p_i)+G_{pi} = 0 \quad (6)$$

stating that the vapour pressures at all surfaces, except those where surface condensation or drying takes place, equal the vapour pressure in the zone. With only outside air ventilation and G_{aei} written as $n.V_i$, n being the outside air ventilation rate (h⁻¹), the hygric balance further simplifies to:

$$p_i = p_e + \frac{462\cdot T_i\cdot(G_p-\Sigma\beta_{ki}\cdot A_{ki}\cdot(p_i-p'_{ki}))}{n\cdot V_i} \quad (7)$$

Finally, if neither surface condensation nor surface drying are present, one gets the extremely simple steady-state expression:

$$p_i = p_e + \frac{462\cdot T_i\cdot G_{pi}}{n\cdot V_i} \quad (8)$$

saying that, if on average no air drying takes place, the mean inside vapour pressure has as its lowest value the mean outside vapour pressure. The difference between both increases when more vapour is produced and less ventilation is present ($n.V_i$). For a given construction type, the total leakage area now is more or less proportional to the envelope surface. Therefore, the mean basic ventilation rate in naturally ventilated buildings is fairly independent of the building volume, and ventilation may be divided into a "ventilation rate, determined by inside–outside temperature differences, wind direction, wind velocity and inhabitants' behaviour" and the "inside air volume". In that case, with a given ventilation rate, a smaller volume means an increase of the difference in inside – outside vapour pressure.

Equation 7 shows that with surface condensation or surface drying, the influences of vapour production and ventilation are both reduced (see Figure 2).

Consequences

The simple formulas 1 and 2 show in a direct way that the chance of mould problems and

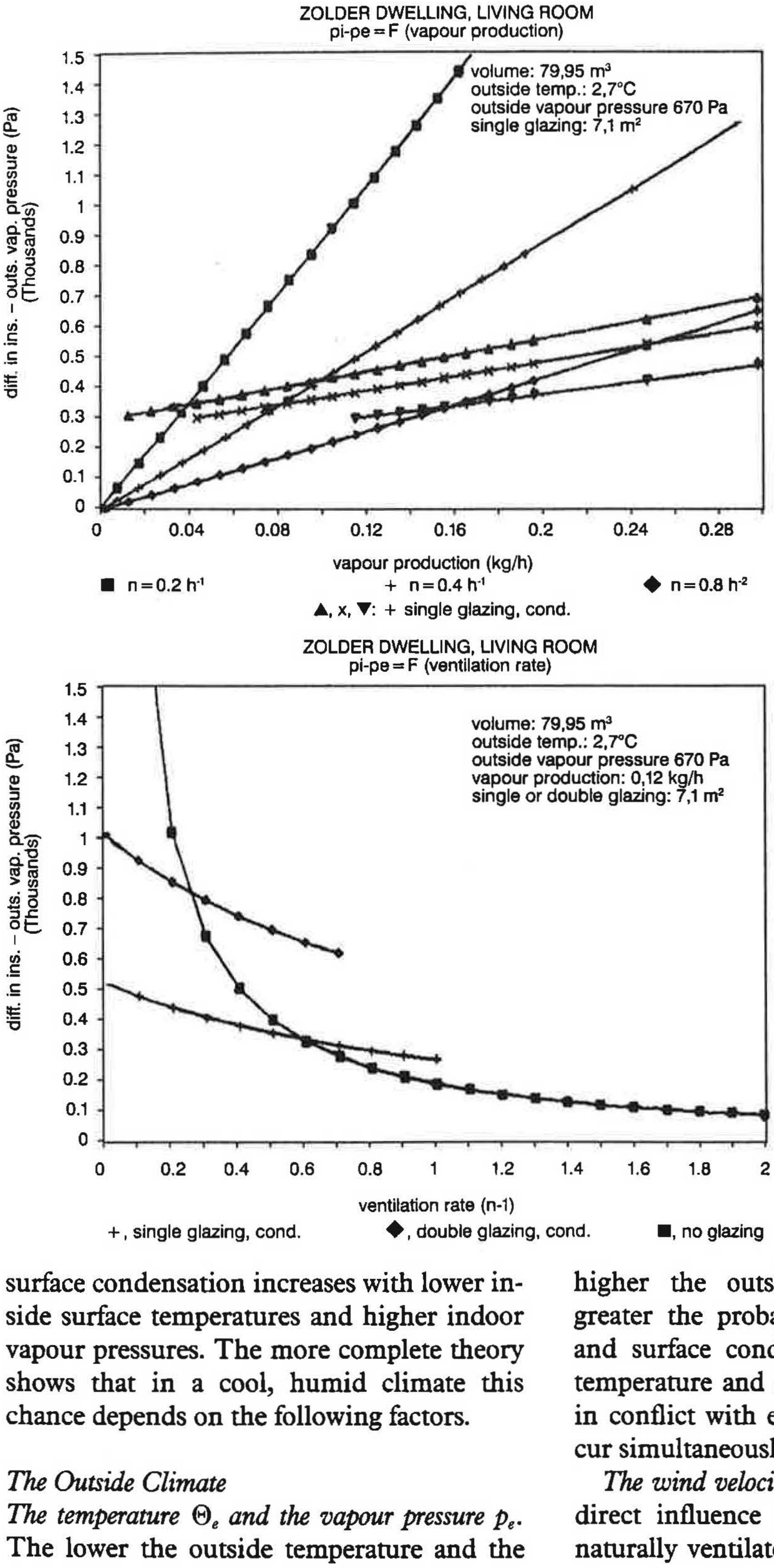


Fig. 2

surface condensation increases with lower inside surface temperatures and higher indoor vapour pressures. The more complete theory shows that in a cool, humid climate this chance depends on the following factors.

The Outside Climate

The temperature Θ_e *and the vapour pressure* p_e. The lower the outside temperature and the higher the outside vapour pressure, the greater the probability of mould problems and surface condensation. However, a low temperature and a high vapour pressure are in conflict with each other: they cannot occur simultaneously.

The wind velocity. The wind velocity has a direct influence on the ventilation rate in naturally ventilated buildings: the lower the wind velocity, the lower the ventilation rate n and the greater the probability of mould problems and surface condensation.

The Building Design and Fabric

The air volume of the building. The smaller the air volume for a given ventilation rate in naturally ventilated buildings, the lower the ventilation flow, the higher the inhabitant density and the greater the probability of mould problems and surface condensation.

The thermal quality of the envelope. The lower the temperature factors, the greater the probability of mould problems and surface condensation. A low temperature factor implies low thermal resistances R', thermal bridging, a lack of air tightness and low surface film coefficients h_i.

The airtightness of the envelope. The basic ventilation rate n_b is a direct consequence of the limited airtightness of the building envelope. The higher the air tightness, the lower n_b and the greater the probability of mould problems and surface condensation.

The surface film coefficient h_i. Although already mentioned under thermal quality, h_i is worth considering separately. Its value depends on the convective and radiative heat exchanges between the point considered and the surrounding air and surfaces. The radiative part in particular is influenced by the overall thermal quality of all surrounding envelope parts, by the outside wall-total wall ratio and by screening effects. The worse the thermal quality of these envelope parts, the higher h_i. The more effective the screening, i.e. by furniture, the lower the radiative exchanges, the lower the h_i- value and the greater the probability of mould problems and surface condensation.

The inside temperature Θ_i. Θ_i is envelope coupled. In fact, if the building is poorly insulated, maintaining a sufficiently high temperature becomes so energy-consuming and so expensive, that the occupants cannot manage it. The consequence is a low inside temperature in the intermittently occupied rooms. The lower the inside temperature in these rooms, the greater the probability of mould problems and surface condensation.

The vapour production G_p. A high vapour production may be a consequence of other building-fabric-coupled moisture problems, such as rain penetration, rising damp, leakages. The higher the vapour production, the greater the probability of mould problems and surface condensation.

The internal finishes. The internal finish and the dust lying on it forms the substrate for mould germination and growth. Some paints and wall papers are more sensitive than others: they require a lower threshold relative humidity "a_w", increasing the probability of mould problems, but *not* of surface condensation.

The Occupants' Behaviour

The inside temperature Θ_i. The inside temperature not only depends on the thermal quality of the fabric but also on the heating habits. The less the building is heated, the lower the inside temperature and the greater the probability of mould problems and surface condensation.

The ventilation rate. Occupants have a substantial effect on excess ventilation by permanent airing, opening windows, etc. The less excess ventilation, the lower the resulting ventilation rate and the greater the probability of mould problems and surface condensation.

The vapour production G_p. The higher the moisture production, the greater the probability of mould problems and surface condensation. Living in and using a dwelling inevitably means vapour production. The overall vapour release is directly linked to the number of occupants, the time they stay at home and the layout choices made: one cannot blame people for having too many children for the dwelling they use, of being unemployed, of having no laundry drying room, etc.

Links with Energy Use for Heating

The parameter summary makes clear that in cool, humid climates, mould problems and surface condensation are most likely to occur in badly insulated dwellings, i.e., in houses with a high basic energy demand. Moreover, avoiding mould in these buildings demands a substantial ventilation rate, especially when the dwellings are used intensively. This means a still higher demand. Lowering the mean inside temperature Θ_i to economize on energy spending is also inevitably counteracted by a further increase in ventilation need. The result of all these measures is a total loss of energy demand elasticity.

Insulated houses may give rise to complaints if thermal bridges are left. These have a net energy impact, multiplying in negative cases the conductive heat losses with a factor of 1.3 or more. To avoid mould, substantial ventilation is needed, increasing the energy demand still further.

It is clear that minimizing mould complaints, realizing a low energy demand and having good thermal comfort and acceptable IAQ all point in the same direction: "the construction of well insulated, thermal bridge-free, correctly ventilated buildings, with heating in each thermal zone". The Guidelines and Practice Report gives four performance criteria:

(1) a sufficient overall thermal quality: a minimum mean thermal resistance of the outer walls ≥ 2 m^{2}K/W;
(2) no unacceptable thermal bridges: temperature factor ≥ 0.7 and linear thermal transmittances as low as possible;
(3) implementing a ventilation system that guarantees a permanent ventilation rate ≥ 0.5 ach;
(4) a heating device in each day-time and night-time room.

These criteria are valid only in cool, humid climates, where heating is dominant and air drying absent. In warm or hot climates, where cooling and air drying are normal practice, other performance criteria play a role, placing more emphasis on the inside finishes, on good functioning of the air driers, etc.

For cold climate countries, it may be strange to stress thermal insulation. In cool climates, however, building practice is such that insulation became normal practice only during the second half of the 1970s, after the first oil crisis. Older dwellings are not insulated at all.

The Zolder-Lindeman Case Study

The Zolder-Lindeman case study provided the opportunity of judging the causes of mould problems and surface condensation in a typical post-war social dwelling environment. It also made it possible to evaluate retrofitting actions according to the performance rules given, by intensive field measurements before and after.

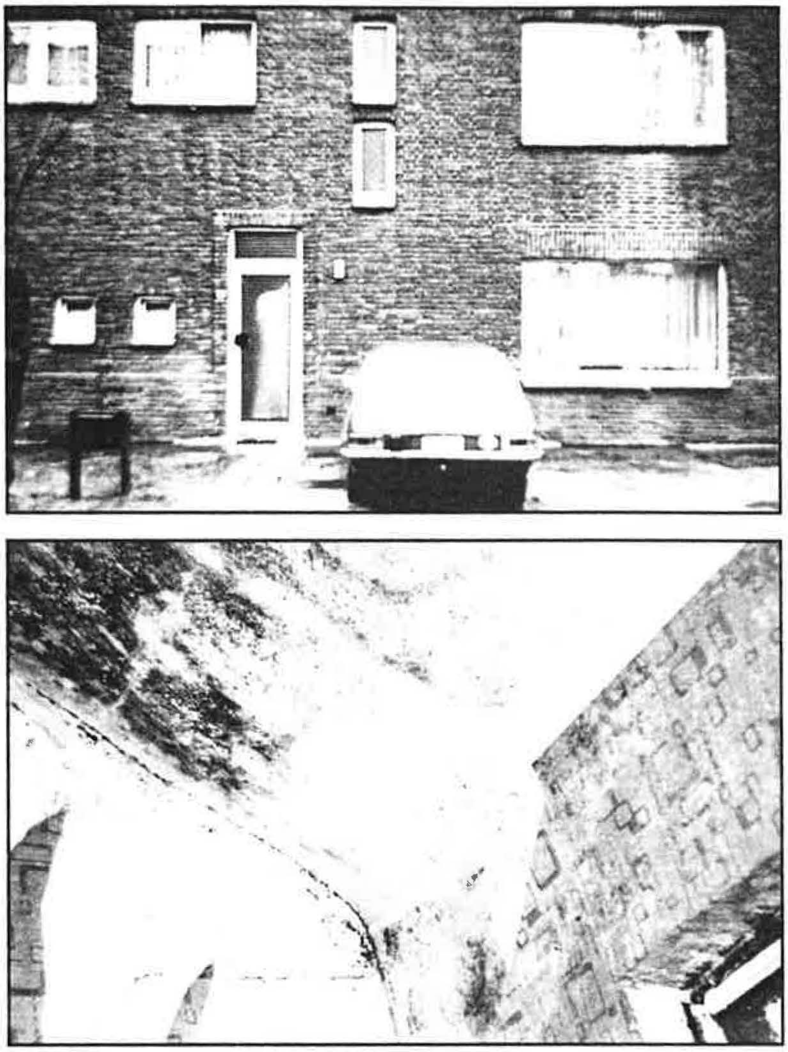
General

Zolder is located in the Flemish part of Belgium, some 200 km east of the North Sea coastline. Geographical situation:

longitude	:	5° 20'
latitude	:	51° 05'
height	:	50 m above sea level.

The climate is cool and humid with a yearly mean temperature of 9.8 °C and a yearly mean RH of 85.2%. The lowest monthly mean winter temperature is 2.7 °C, with rare cold spells reaching a daily mean temperature of -10 °C. The highest monthly mean summer temperature rises to some 16.8 °C, with rare warm spells, peaking at a daily mean temperature of 25 °C. The relative humidity fluctuates between 77.8% in May and 92.7% in December. The yearly rainfall scatters

Fig. 3



around ≈ 800 mm/m². The Lindeman estate comprises some 140 dwellings. It was built shortly before the end of the 1940s by the "Kempische steenkoolmijnen NV". The 2-story houses with cellar and loft space are constructed with masonry cavity walls, a tiled roof and single glass windows in metallic frames. They were coalfire heated, with a chimney in each room (Figure 3).

In the early 1980s, intensive retrofitting actions took place: a reorganization of the ground floor, combining the kitchen and the small living room into one larger living room, transforming the laundry room into a kitchen and adding a bathroom (Figure 4). All chimneys, except one, were pulled down and the coal fires replaced by gas-fired central heating with radiators in each room. The single-glazed, leaky metal windows were replaced with airtight, double-glazed PVC-windows. The windows in all rooms, except for the streetside window of the living room, have a pivoting part. The kitchen was equipped with an exhaust hood above the cooking gas stove. No ventilation system was incorporated (no grids in windows and doors, no vertical vents in bathroom and kitchen) nor was any further thermal upgrading, except double glazing, done (no loft floor insulation, no cavity filling).

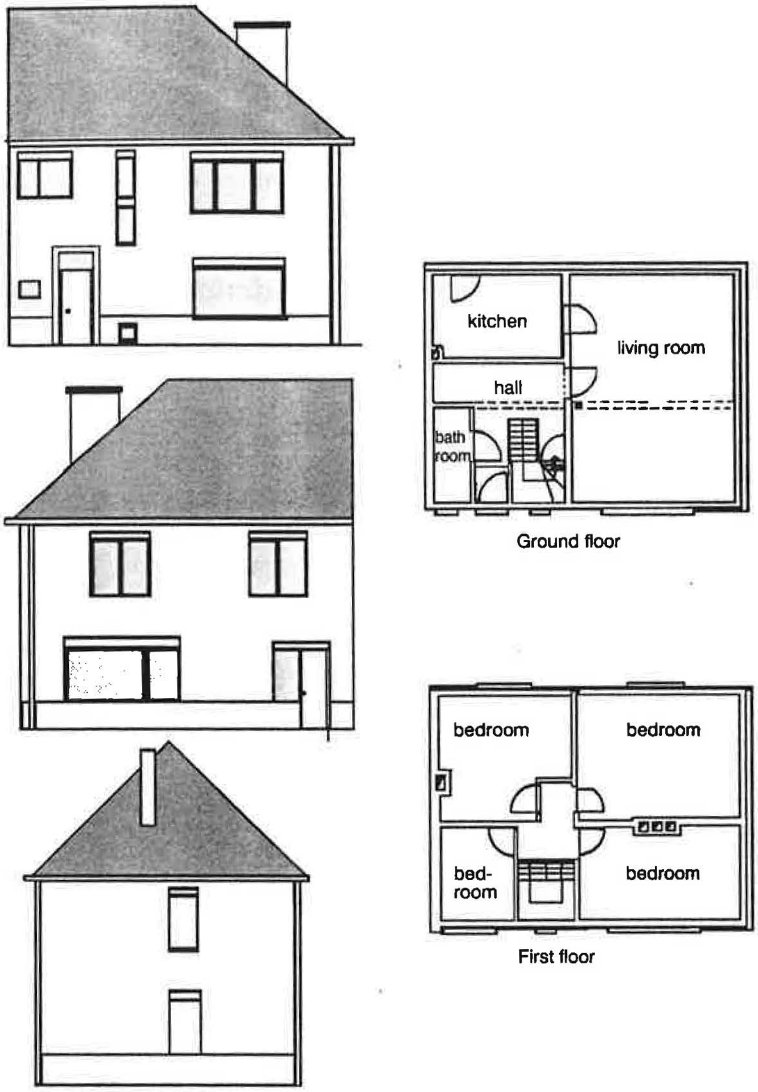


Fig. 4

Complaints

Quickly after the retrofit, the first complaints about odours, mould and moisture occurred. An enquiry in 110 houses of the estate, organized in 1987, revealed that all houses had wet cellar walls, while 75 showed more or less severe mould damage (Table 1). Health problems, attributed by the inhabitants to the poor state of their dwelling, were noted in 26 of the 75 cases with mould.

Mould Species

These were analysed in 3 dwellings (Table 2 shows the species occurring most frequently). The species on the samples differed from one dwelling to another, from one room to another and within the same room from one finish to another.

Causes of the Problem

To diagnose the causes, three houses were taken as reference. One was a retrofitted end-house, inhabited by two pensioners and having all the problems mentioned in Table 1. As an antimould measure, proposed by the housing society before the research started, double glazing was changed for single glazing. The change was unsuccessful.

Table 1 Mould complaints in the Lindeman Estate (1987 enquiry); 75 problem cases out of 110 dwellings visited.

Room	Mould on	Number	% of 75
bedroom	lintels, entire ceiling, corners	64	85
kitchen	ext.wall/ceiling	26	35
bathroom	ext.wall/ceiling	27	36
living room	ext.wall/corners	22	29
hall	ceiling/walls	25	33

Table 2 Most commonly isolated mould species in three houses of the Lindeman Estate.

Species	in x of the 10 samples x=..
Ulocladium Consortiale	7
Aspergillus Fumigatus	6
Cladesporium Cladesporoides	6
Penicillium Cyclopium	4
Mucor	4

In the dwelling, inside temperatures, RH's and resulting temperatures in all rooms, surface temperatures on 22 spots in the living room and 2 spots in a bedroom, densities of heat flow rate on 1 spot in the living room and 2 spots in the bedroom have been logged continuously (logging interval:15 minutes) from the winter 1986-1987 until the spring of 1989. These measurements were made for the climatic data with hygrothermographs, Rotronic Hygromer RH and T-sensors and Cu-Co thermocouples mounted in white ping pong balls, for the surface temperature with Cu-Co thermocouples, and for the densities of heat flow with TNO-WS31 heatfluxmeters. All data were collected by a HP-datalogging system, linked to a PC. The outside temperature and RH were logged in the garden, 1.5 m above ground level.

Inside Climate

The measuring results (see Table 3) give the weekly mean values compared to the weekly mean outside temperature. Although the correlation factor r^2 may be weak, Θ_e is the only variable with a systematic influence. In fact, for the inside temperature, the constant of the correlation line is lower the less heating there is and its slope steeper the less heating and the more ventilation are present. For the difference in inside–outside vapour pressure, the constant of the correlation line is lower the less vapour production and the more ventilation, while its slope steepens the more the ventilation flow increases with rising outside temperature. All other variations and the scatter around the mean line are caused by randomly distributed influences. In these, because of the weekly mean, hygric inertia is of minor importance (although it explains the hysteresis on a yearly basis in the inside vapour pressures, the inside–outside differences being larger for the same mean vapour production and the same mean ventilation rate in autumn than in springtime).

Comparing the results with the mean winter references for normally heated and venti-

Table 3 Inside temperature and difference in inside – outside vapour pressure in the dwelling, before any remedial measure in the frame of the research work took place.

Room	$\Theta_i = f(\Theta_e)$ °C	$p_i - p_e = f(\Theta_e)$ Pa
Living room	$17.8 - 0.08.\Theta_e$ ($r^2 = 0.17$)	$562\text{-}4.7.\Theta_e$ ($r^2 = 0.25$)
Kitchen	$19.2 - 0.09.\Theta_e$ ($r^2 = 0.19$)	$506\text{-}3.8.\Theta_e$ ($r^2 = 0.14$)
Bathroom	$13.6 - 0.01.\Theta_e$ ($r^2 = 0.00$)	$478\text{-}4.0.\Theta_e$ ($r^2 = 0.20$)
Downstairs hall	$13.7 + 0.16.\Theta_e$ ($r^2 = 0.39$)	$327\text{-}6.3.\Theta_e$ ($r^2 = 0.29$)
Upstairs hall	$12.2 + 0.15.\Theta_e$ ($r^2 = 0.10$)	$374\text{-}4.2.\Theta_e$ ($r^2 = 0.25$)
Bedroom 1	$11.5 + 0.16.\Theta_e$ ($r^2 = 0.32$)	$356\text{-}9.7.\Theta_e$ ($r^2 = 0.35$)
Bedroom 2	$10.2 + 0.29.\Theta_e$ ($r^2 = 0.68$)	$401\text{-}1.0.\Theta_e$ ($r^2 = 0.10$)
Bedroom 3	$10.4 + 0.42.\Theta_e$ ($r^2 = 0.41$)	$373\text{-}3.3.\Theta_e$ ($r^2 = 0.43$)
Bedroom 4	$8.1 + 0.38.\Theta_e$ ($r^2 = 0.70$)	$399\text{-}8.6.\Theta_e$ ($r^2 = 0.39$)
Cellar	$10.3 + 0.31.\Theta_e$ ($r^2 = 0.55$)	$217\text{-}15.\Theta_e$ ($r^2 = 0.29$)

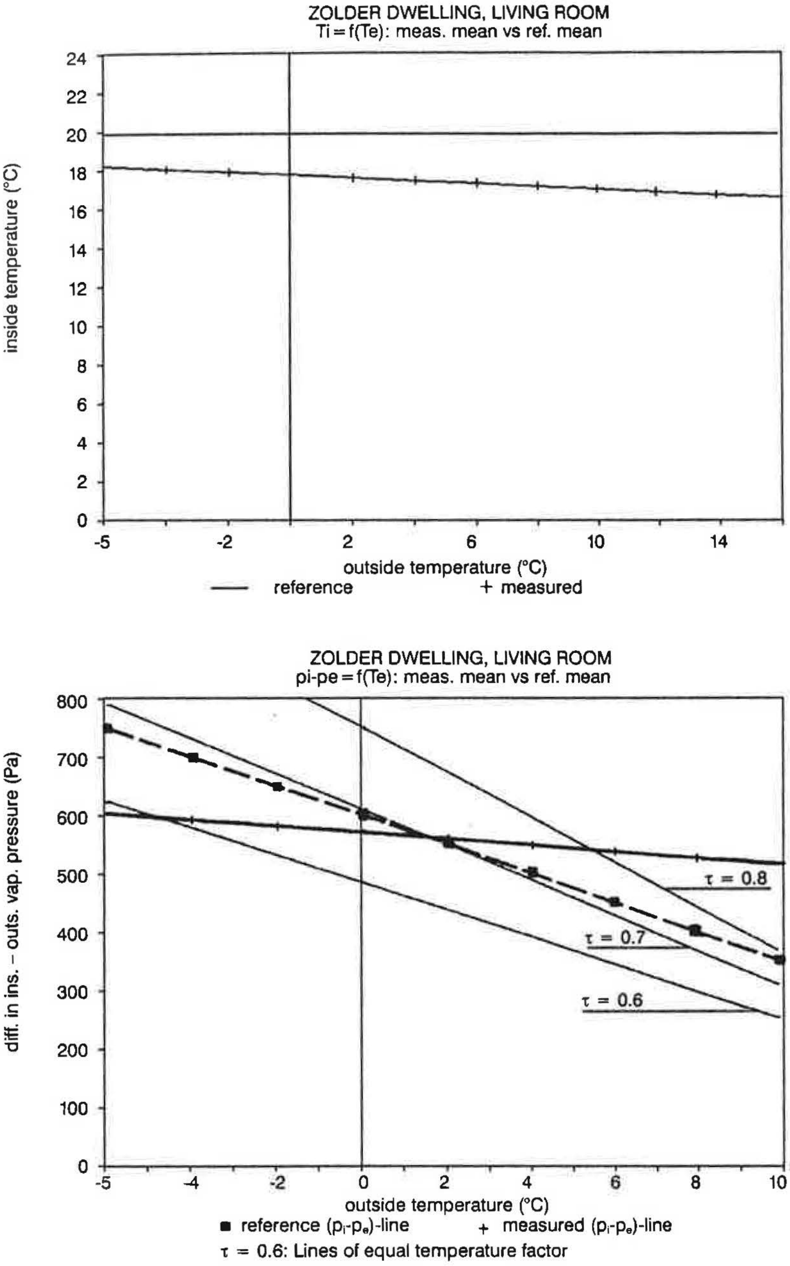


Fig. 5

lated dwellings, as calculated from a large set of measuring data (Figure 5):

day-time-rooms:

$$\Theta_i \geq 20\ °C,\ p_i\text{-}p_e = 592\text{-}24.2.\Theta_e$$

night-time-rooms:

$$\Theta_i \geq 15\ °C,\ p_i\text{-}p_e = 303\text{-}13.0.\Theta_e$$

the dwelling is poorly heated: a winter living room temperature lower than 17.8 °C and bedroom temperatures around 8 to 12 °C instead of ≥ 20 °C and ≥ 15°C. This could be a consequence of the deficient thermal insulation, making full heating much too expensive for two pensioners!

Also the difference in inside–outside vapour pressure seems high: 539-4.7.Θ_e compared to 592-24.2.Θ_e, i.e. higher than the reference for mean outside temperatures above 2.7 °C! This could be caused by poor ventilation, by a considerable moisture production, or by vapour transfer from the wet cellar to the living space. The latter was excluded after an analysis of the measurements, showing that the gas boiler underpressurized the cellar. The second possibility seemed rather impossible, because the dwelling was inhabited by only two retired people. The first cause appears to be the most likely.

Finally, from the lines of equal τ-value in Figure 5 it can be seen that to avoid mould in the cold season for the given inside climate, a temperature factor >0.78 is needed in the living room and in the kitchen. In the bedrooms, the RH already exceeds 80%, the mean a_w-limit for the development of mould on a substrate, making mould problems there inevitable!!

Insulation Quality

The insulation quality of the envelope has been evaluated by calculations and measurements.

Calculated results

Compactness : 1.34 m (= ratio between volume and envelope surface)

Mean U-value: $U_m = 2.0$ W/(m^2.K)

Current Flemish legislation requires a mean U-value 0.78 W/(m^2.K) for social houses with a compactness 1.34 m, i.e. 3 times lower than the present value; the dwellings of the Lindeman estate are in fact real thermal ruins.

Measured results (see Table 4). The high U-values of the cavity wall and the ceiling and the low to very low temperature factors sharply underline the poor insulation quality: the lowest τ-value in the living room is hardly 0.36, while with the actual inside climate, a value $\geq$ 0.78, is needed to avoid mould germination. Mould was in fact present on all spots with a temperature factor lower than 0.7. Where lower than 0.5, surface condensation was regularly visible during the measuring campaign. The U-value of the cavity wall is of particular interest as it was lower in the bedroom than in the living room. The living room is heated, while the bedroom is not. The cavity air, warmed at ground level, rises by stack effect to the second floor and reduces the heat flow there through the inside leaf. As the density of heat flow is measured on the inside surface, this phenomenon is translated in a fictitious higher thermal resistance and a lower U-value. Reinterpreting the measurement results gave a constant thermal resistance 0.27 m^2.K/W of the inner leaf of the cavity wall and a mean cavity temperature Θ of $3.4 + 0.72.\Theta_e$ ($\Theta_e \geq 10$ °C).

Remarkably, the surface film coefficients in the living room and bedroom are clearly lower than the standardized value of 8 W/(m^2.K). The reasons for this are the high ratio outside wall : total wall surface and, for the

Table 4 The measured thermal resistances, U-values, temperature factors and surface film coefficients before the remedial measures (measurements made with heat flow meters and Cu-Co surface temperature sensors).

Dwelling 1	R m^2.K/W	U W/(m^2.K)	τ -	h_i W/(m^2.K)
Living room,				
cavity wall	0.47	1.47 ± 0.1	0.75	6.3
id., behind cupboard	0.36			
id., lower 3D corner	0.45			
id., upper 3D corner	0.60			
Bedroom				
cavity wall	0.66	1.10 ± 0.4	0.72	3.9
ceiling	0.26	2.23 ± 0.05	0.67	5.8

Table 5 Ventilation rate before the retrofit of the early 1980s: calculated results for the living room.

	Wind speed m/s	n h^{-1}
Living room	0	0.3
	4	0.85
	8	2.0
	16	4.9

Table 6 Pressuration test on the retrofitted dwelling.

Measure	n_{50} h^{-1}
Reference	5.1
Hood in the kitchen airtightened	4.8
Cellar airtightened	3.9
Entry to the loft space airtightened	3.2
Joints between doors and floors airtightened	2.1
Windows airtightened	1.0

living room, the poor heating of the second floor.

Ventilation
As with the insulation, the ventilation rate was checked by both calculations and measurements.

Calculated results. Calculations have been made for the situation before the retrofit, with the coalfire-burning and the leaky metallic windows. The results (see Table 5) show that in wintertime the situation was not so bad: a mean ventilation rate not below 0.7 h^{-1} could be expected.

Measured results. A measured value was determined for the retrofitted dwelling by a pressuration test and by interpreting hygrothermograph readings. For the results of the pressuration tests, see Table 6. They show that after the retrofit the overall airtightness became so high (n_{50} = 5.1 h^{-1}), that only controlled natural ventilation or mechanical ventilation could solve the ventilation demand. Sealing all visible leaks even reduces n_{50} to 1 h^{-1}. However, this is not the value at present, except if the inhabitants should have sealed all leaks, which is not the case.

From the exponential decrease in vapour pressure on the hygrothermograph readings in the living room during night-time, a lower ventilation rate limit n_o of 0.17 h^{-1} was estimated. This rate did not take into account hygroscopic inertia, or surface condensation or surface drying. The first introduces an underestimation, the second an overestimation. A ventilation rate of 0.17 h^{-1} is a low value. This, along with the pressure tests, confirmed that poor ventilation and not high vapour production was the cause of the important difference in inside–outside vapour pressure. However, the overall airtightness and the impossibility of cross ventilation in the day zone excluded any attempt to improve the ventilation without losing the already poor thermal comfort.

Conclusions

The causes of mould in the dwelling and, by extrapolation, in the major part of the Lindeman estate, are the very poor insulation quality and the lack of ventilation possibilities, especially since the retrofitting. The last-

Table 7 Effects of the loft floor insulation on the interior air temperatures.

	Before	After
Living room	$17.8\text{-}0.08.\Theta_e$ ($r^2=0.17$)	$17.7+0.09.\Theta_e$ ($r^2=0.14$)
Kitchen	$19.2\text{-}0.09.\Theta_e$ ($r^2=0.19$)	18.7
Bathroom	13.6	$16.1\text{-}0.07.\Theta_e$ ($r^2=0.07$)
Downstairs hall	$13.7+0.16.\Theta_e$ ($r^2=0.39$)	$14.0+0.05.\Theta_e$ ($r^2=0.16$)
Bedroom 1	$11.5+0.16.\Theta_e$ ($r^2=0.32$)	$13.2+0.12.\Theta_e$ ($r^2=0.68$)
Bedroom 2	$10.2+0.29.\Theta_e$ ($r^2=0.68$)	$13.3+0.16.\Theta_e$ ($r^2=0.69$)
Bedroom 3	$10.4+0.42.\Theta_e$ ($r^2=0.41$)	$13.0+0.36.\Theta_e$ ($r^2=0.70$)
Bedroom 4	$8.1+0.38.\Theta_e$ ($r^2=0.70$)	$13.3+0.07.\Theta_e$ ($r^2=0.50$)

mentioned cause is also the reason for the deterioration in the situation from the early 1980s onwards.

Remedial Measures

The remedial measures in the dwelling focused on the causes of the problem: improving the deficient thermal insulation and increasing the mean ventilation rate.

Measure 1: *Improving the loft floor insulation with 12 cm thick mineral wool slabs.*
The effects were a drop in mean U-value of the dwelling from 2.0 to 1.46 W/(m^2.K) (calculated result), an increase in thermal resistance of the ceiling in all bedrooms from 0.26 to 3.3 m^2.K/W (measured result), an increase of the temperature factor τ_{hi} of the ceiling from 0.67 to 0.85 (measured), a decrease of the surface film coefficient h_i at the ceiling from 5.8 to 1.6 W/(m^2.K) (measured) and a clear increase in air temperature in all bedrooms (see Table 7). Because of this increase in air temperature, the RH fell (in bedroom 2 from 79% to 68%). That result and the temperature factor of the ceiling becoming high enough to eliminate any further mould germination, solved the problem in the bedrooms. In fact, after cleaning and repainting, no moulds reappeared.

Nevertheless, the ceiling temperature factor did not rise linearly with thermal resistance: the lower h_i-value counterbalanced, to some extent, the thermal resistance influence. This lower h_i-value resulted from a more restricted convection but especially from the turnover after insulation from radiative gains (the other outside wall surfaces warmer than the ceiling) to radiative losses (the other outside wall surfaces colder than the ceiling).

Measure 2: *Replacing single glazing by double glazing.*
The effects were a drop in mean U-value of the dwelling from 1.46 to 1.23 W/(m^2.K) (calculated), an increase in air temperature in all rooms (Table 8) and no change in inside – outside vapour pressure difference, except in the pensioner's bedroom (= bedroom 2): there, an increase from $401\text{-}1.0.\Theta_e$ (Pa, $r^2 = 0.10$) before to $505\text{-}4.2.\Theta_e$ (Pa, $r^2 = 0.17$) after was seen. The higher air temperature, however, prevented a worsening of the situation: the mean RH rose only from 79% to 80%. The higher difference in inside–outside vapour pressure in that particular room could be linked to the loss of air drying capacity through condensation on the single glazing. In all other rooms, RH dropped.

Measure 3: *Internal insulation in the living room: 3 cm PS, with a gypsum board lining.*
The effects were a drop in mean U-value of the dwelling from 1.23 to 1.15 W/(m^2.K) (calculated), an increase in thermal resistance of the cavity wall from 0.43 to 1.23 m^2.K/W (measured), an increase in temperature factor

Table 8 Effects of double glazing on the interior air temperatures.

	Before	After
Living room[a]	$17.7 + 0.09.\Theta_e$ ($r^2 = 0.14$)	18.5
Kitchen	18.7	$19.1 + 0.07.\Theta_e$ ($r^2 = 0.14$)
Bathroom	$16.1\text{-}0.07.\Theta_e$ ($r^2 = 0.07$)	$18.8 + 0.37.\Theta_e$ ($r^2 = 0.87$)
Downstairs hall	$14.0 + 0.05.\Theta_e$ ($r^2 = 0.16$)	$14.2 + 0.08.\Theta_e$ ($r^2 = 0.50$)
Bedroom 1	$13.2 + 0.12.\Theta_e$ ($r^2 = 0.68$)	$14.7 + 0.11.\Theta_e$ ($r^2 = 0.82$)
Bedroom 2	$13.3 + 0.16.\Theta_e$ ($r^2 = 0.69$)	$14.9 + 0.07.\Theta_e$ ($r^2 = 0.73$)
Bedroom 3	$13.0 + 0.36.\Theta_e$ ($r^2 = 0.70$)	$14.6 + 0.23.\Theta_e$ ($r^2 = 0.76$)
Bedroom 4	$13.3 + 0.07.\Theta_e$ ($r^2 = 0.50$)	$14.5 + 0.23.\Theta_e$ ($r^2 = 0.23$)

[a] including the effect of the inside insulation (see measure 3).

Table 9 Effects of the natural ventilation system on the interior air temperatures and on the difference in inside – outside vapour pressure.

	Before		After	
	Θ_i	$p_i - p_e$	Θ_i	$p_i - p_e$
Living room	18.5	$562\text{-}4.7.\Theta_e$ ($r^2=0.25$)	$18.7\text{-}0.19.\Theta_e$ ($r^2=0.21$)	$525\text{-}35.\Theta_e$ ($r^2=0.21$)
Kitchen	$19.1+0.07.\Theta_e$ ($r^2=0.14$)	$506\text{-}3.8.\Theta_e$ ($r^2=0.14$)	$21.0\text{-}0.30.\Theta_e$ ($r^2=0.41$)	$539\text{-}41.\Theta_e$ ($r^2=0.36$)
Bathroom	$18.8+0.37.\Theta_e$ ($r^2=0.87$)	$488\text{-}4.0.\Theta_e$ ($r^2=0.20$)	$14.4+0.38.\Theta_e$ ($r^2=0.38$)	$279+5.0.\Theta_e$ ($r^2=0.07$)
Downstairs hall	$14.2+0.08.\Theta_e$ ($r^2=0.50$)	$327\text{-}6.3.\Theta_e$ ($r^2=0.29$)	$13.1+0.33.\Theta_e$ ($r^2=0.17$)	$142+1.0.\Theta_e$ ($r^2=0.23$)
Bedroom 1	$14.7+0.11.\Theta_e$ ($r^2=0.82$)	$356\text{-}9.7.\Theta_e$ ($r^2=0.35$)	$11.1+0.45.\Theta_e$ ($r^2=0.48$)	$118+16.\Theta_e$ ($r^2=0.13$)
Bedroom 2	$14.9+0.07.\Theta_e$ ($r^2=0.73$)	$401\text{-}1.0.\Theta_e$ ($r^2=0.10$)	$12.4+0.33.\Theta_e$ ($r^2=0.39$)	$322+17.\Theta_e$ ($r^2=0.17$)
Bedroom 3	$14.6+0.23.\Theta_e$ ($r^2=0.76$)	$373\text{-}3.3.\Theta_e$ ($r^2=0.43$)	$13.5+0.22.\Theta_e$ ($r^2=0.63$)	$187\text{-}5.0.\Theta_e$ ($r^2=0.30$)
Bedroom 4	$14.5+0.23.\Theta_e$ ($r^2=0.23$)	$399\text{-}8.6.\Theta_e$ ($r^2=0.39$)	$12.8+0.34.\Theta_e$ ($r^2=0.17$)	$131+16.\Theta_e$ ($r^2=0.02$)

τ of the wall from 0.75 to 0.82 (measured), a decrease in surface film coefficient h_i at the wall from 6.3 to 3.6 W/(m^2.K) (measured), no change to a slight decrease of the temperatures on adjacent 2- and 3-dimensional geometries, a small increase in air temperature and no changes in the difference in inside – outside vapour pressure in the living room.

After all, the inside insulation action was not a convincing retrofit: mould disappeared on the insulated wall but the situation deteriorated on the adjacent noninsulated parts. This was predicted, the social housing company was informed beforehand, but, nevertheless, they went ahead, the motivation being that inside insulation was less costly than outside insulation.

Measure 4: *Installing a natural ventilation system: grids in windows and doors, dimensioned according to the Dutch standards NEN 1087 and NPR 1088.*

The effects were a decrease in air temperature, except in the day-time rooms, and an overall decrease in inside–outside vapour pressure (Table 9). This caused such a significant drop in inside RH, that the chance of persisting mould problems was finally reduced to practically 0 in the whole dwelling. In fact, a control showed that, with the ventilation grids open, the RH on surfaces with a τ-value ≥ 0.7, definitively dropped under 80%.

Contrary to all theories predicting a negative slope, the $\Delta p_{ie}(\Theta_e)$- lines show a positive slope in 5 of the 8 rooms. This could be explained by the slow hygroscopic moisture release from furniture, finishes and walls, during the first weeks the ventilation system was in operation.

The influence of hygroscopicity on a short-term basis was already proved by tests on peak ventilation: opening the window in the bedroom each day during a restricted time interval ($\approx$ 15 min.) appeared totally inefficient. After closing, the inside vapour pressure quickly returned to its preopening level (Figure 6).

A multivariational analysis on all measuring results confirmed that in all rooms, outside air ventilation became more important than inter-room airflow after the ventilation system was mounted and in use.

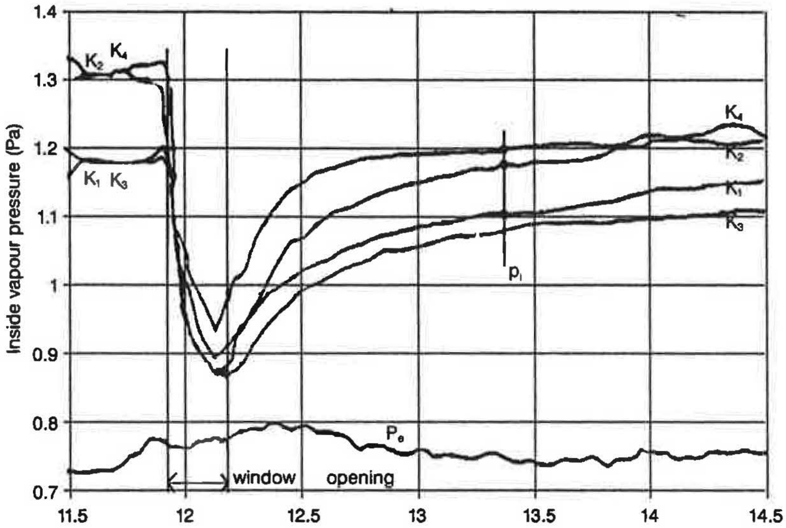


Fig. 6 The effect of the hygroscopic inertia on the inside vapour pressure: return to the level after a short ventilation in the bedrooms.

K_1, K_2, K_3, K_4: bedrooms
p_e: outside vapour pressure (Pa)

Conclusions

The one dwelling showed that insulating the loft space floor, replacing the single glazing by double glazing and improving the ventilation by installing a natural ventilation system were three efficient remedial measures in combating the mould problem. These three measures should be implemented in all dwellings of the estate. Further improvements could include outside insulation and forced ventilation. Outside insulation is tested in the second dwelling, and forced ventilation, as an alternative to natural ventilation, is tested in the third.

The positive influence of thermal insulation in the case described was stressed by the need for only partial heating. This couples to the good insulation the advantage of an overall increase in inside temperature in the non-heated and therefore mould-sensitive rooms. Partial and intermittent heating was the only way for the two pensioners to keep the heating bill affordable. The partial heating is also reflected in the ventilation measure results: with the system in use, a drop in inside temperature in all non-heated rooms was measured. One can imagine that people in the lower income group budget a fixed amount for heating. If the dwelling is well insulated, a fixed budget and accompaning low energy use results in an acceptable thermal comfort and a low risk of mould and condensation problems. If the dwelling is poorly insulated, the same budget and low energy use give comfort problems and almost certainly mould and condensation problems.

It can also be argued that the diagnosis and retrofitting work in the Zolder case study proved the correctness of 3 of the 4 practice rules to avoid mould problems in cool, humid climates:

(1) a sufficient overall thermal quality: a minimum mean thermal resistance of the outer walls ≥ 2 m².K/W;
(2) no unacceptable thermal bridges: temperature factor ≥ 0.7 and linear thermal transmittances as low as possible;
(3) implementing a ventilation system that guarantees a permanent ventilation rate ≥ 0.5 ach.

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