THE K 30 LOW ENERGY BUILDING SYSTEM : A THEORETICAL ANALYSIS AND EXPERIMENTAL VERIFICATION OF PERFORMANCES

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1. Introduction

Energy conservation as a lever to introduce new technologies, new solutions, a better quality in the building industry, the K 30 building system may be seen as a step in that direction. From the first scetches, the major goals were:
- the implementation of an improved technology
- using non-traditional materials
- producing a very energy efficient building
- with minimal maintenance costs

The whole design, including a prototype house, has been tested extensively. That resulted in a building system with well-known performances

The work was sponsored by the government's office for scientific policy, in the frame of the R-D energy program, and by the company involved.

2. The system (2)

The K 30 system consists of a modular, load bearing frame, composed of steel columns and wooden beams or trusses, spanning 3,9 m and mounted on a precast concrete slab, with underside insulation (6 cm PSe), the slabs being laid above a crawl space (fig. 1). The outside skin is composed of wall-, window-, flat roof - and sloped roof elements.

fig. 1

Composition:

WALLS, fig. 2.
. outside leaf in white-gray polyester concrete (PC), d = 23 mm.
. cavity, d = 52 mm.
. PS-insulation, d = 150 mm.
. inside leaf, a gypsum board - cavity-gypsum board sandwich, with a polyester laminate (PL) finish, the cavity being used for electrics and plumbing

WINDOWS
. triple glazed PU-elements

FLAT ROOF, fig. 3.
. sandwich PL, 3,5 mm - PU, 170 mm - PL , 3,5 mm stiffened with wooden joist

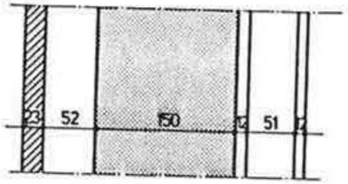

fig. 2 walls

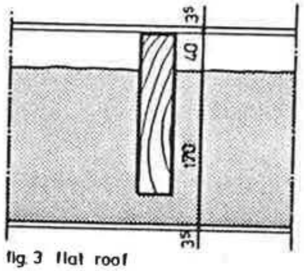

fig. 3 flat roof

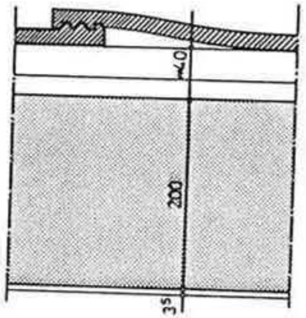

fig. 4 sloped roof.

SLOPED ROOF, fig. 4
. joists, embedded in PU, 200 mm. with an inside PL-cladding and an outside dark gray concrete tiles covering

For the inside partition walls "gypsum-particle board/cavity/gypsum-particle board" elements are used, both sides PL-finished.

The loft spaces of the sloped roofs are integrated in the inside volume, creating a charming variety in room form and look.

The prototype house was electrically heated, using low temperature radiators. Provided was a mechanical ventilation system, the exhaust air being connected, together with the kitchen hood, to a heat recovery unit. Hot water was produced separately, with an electrical boiler in the kitchen and the bathroom.

3. The physical performances (3,4)

3.1. Material properties

Non-traditional materials are:
- polyester concrete (PC), a mixture of sand, fine gravel and polyester resin
- polyester laminate (PL)

Thermally important are:
- the PU-foam, sprayed in factory, d = 170 to 200 mm
- PS, used in roomhigh blocks, d = 150 mm

Measured: volumic mass (ρ), specific heat (c), thermal conductivity (λ), moisture uptake during immersion (Δw), diffusion resistance ratio (μ), capillar absorption coefficient (A)

Results: TABLE 1

MATERIAL	ρ	c	λ ($\theta_m = 20°C$)	Λw	μ ($\theta_m = 25°C$,	μd $\phi m = 60$ à 86%)	Λ
	kg/m^3	$J/(KgK)$	$W/(mK)$	kg/m^3	-	m	$kg/(m^2 s^{0,5})$
PC	2280	935	3,4	0	∞	-	0
PL	1390	-	-	~ 0	-	38,2	0
PS	22,7	-	$0,0335+2,3.10^{-3}\psi$ $\psi \leqslant 6,6\%\ m^3/m^3$	$\leqslant 66$	-	-	0
PU	39,0	-	$t = 0$ 0,018 $t = \infty$ 0,025	-	37	-	0

Table 1: physical properties of the non-traditional and insulating materials, used in the K 30 system

PC appears as a non-capillar, vapourtight concrete, with high thermal conductivity.
PL works as an effective vapour barrier class 3 quality (Belgian standards - class 3 : $25\ m \leqslant \mu d < 200\ m$).
PS and PU are both good insulating materials. Nevertheless, the very low starting λ-value for PU may rise with time until an equilibrium value of $\sim 0,025\ W/(mK)$.

3.2. Wall and roof elements

The detailed hygrothermal evaluation of the outside wall, flat roof and sloped roof elements referred to: the U-value, the steady harmonic thermal properties, hygrothermal stress and strain, the moisture balance, thermal bridges.

Calculations were done with the "WAND"- and "KOBRU 82"- software packages (1).

The U-value was also checked experimentally in the test-house, using long lasting HFM-measurements. Stress and strain and moisture behaviour have been controlled by visual inspection.

Results

U-values $(W/(m^2K))$

WALL (fig. 1.)	calculated:	$0,205 \pm 0,0105$ $(0,033 \leqslant \lambda_{ps} \leqslant 0,04\ W/(mK))$
	measured:	$0,19 \pm 0,024$ (mean value, 5 - 95% limits)
FLAT ROOF (fig. 3.)	calculated:	$0,165 \pm 0,025$ $(0,025 \leqslant \lambda_{PUR} \leqslant 0,035\ W/(mK))$
	measured:	$0,14 \pm 0,01$ (mean value, 5 - 95% limits)
SLOPED ROOF (fig. 4.)	calculated:	$0,145 \pm 0,025$ $(0,025 \leqslant \lambda_{PUR} \leqslant 0,035\ W/(mK))$
	measured:	$0,12 \pm 0,01$ (mean value, 5 - 95% limits)

These U-values and therefore the insulation quality are, compared to normal practice, extremely good. Apart from that, the elements proved to be really airtight, or, the thermal performances remain constant, independent of wind attack.

Steady harmonic properties

Outside wall, flat and sloped roof show almost no thermal inertia, the "24 hours" harmonic thermal resistance being hardly higher than the thermal resistance and the admittance between 0,6 and 1 (heavy construction elements: $Ad = 4$ à $5\ W/(m^2K)$. Through that, some doubts exist about the summer reaction of the system.

Thermal stress and strain

In the prototype house, the outside leafs were light gray coloured, while window and attic elements had a dark brown outside PL-cladding. A non-stationary calculation showed important differences in outside surface temperature, resulting in different strain and shear forces on the joints. Already after 1 year, these showed cracks.

Moisture balance

The analysis revealed no problems with rain penetration, building moisture, surface condensation and interstitial condensation.

Thermal bridges

Potential thermal bridges are:
- the wooden edge beams of the flat and sloped roof elements (fig. 5.)
- the joists in the flat roof elements (fig. 3.)
- all tresholds (fig. 6.)

Of these, only the last worked as real thermal bridges, having a high linear U-value and a low temperature ratio

$$U_L = 0,6 \text{ à } 1,2\ W/(mK)$$
$$\tau \approx 0,34$$

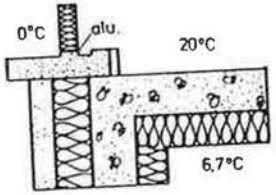

fig. 5 treshold

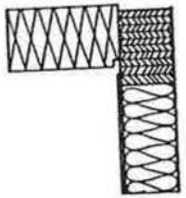

fig 6 edge beam.

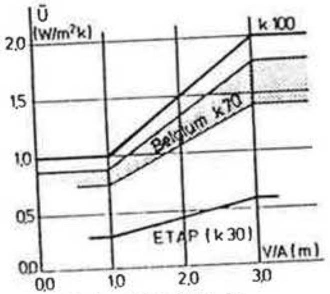

fig 7 insulation level k

3.3. Insulation level of the prototype house (4, 5)

To describe the termal quality of a building, the Belgian standard B 62-301 defines the INSULATION LEVEL K, linking the envelopes mean U-value ($\bar{U}$) to the building compactness C,

$C = \frac{V}{A_\circ}$, with V the heated volume and $A_\circ$ the heated volume envelope surface. The reference line (fig. 7.)

$C \leq 1$	$\bar{U} = 1$
$1 < C < 3$	$\bar{U} = 0,5\ (1+C)$
$C \geqslant 3$	$\bar{U} = 2$

is called insulation level K 100. The lower the K, the better the global thermal insulation. K 30 means: extremely well insulated. If that level was reached really, has been checked in the prototype house by calculations, according to the standards method, and by a 4 weeks co-heating in the non-occupied house (November-December 1983).

During that co-heating, we continuously monitored the outside temperature (θ_e), the equivalent outside temperature on a black, horizontal surface (θ_e^*), the solar radiation on a vertical north and south oriented surface (photovoltaic cells-E_s), the inside temperatures (θ_i) and the heating power Φ_E.

The daily mean climatic data were linked to the 24 hour electricity use Q_E by a function:

$$Q_E = A_\circ + A_1\theta_e + A_2\theta_i + A_3E_s$$

wherein
$$-A_1 = A_2 = \frac{1}{\bar{U}A_\circ + 0,36\ \beta V} \qquad (1)$$

$$\theta_i = \frac{1}{n}\sum_{1}^{n} \theta_i \qquad (2)$$

β, the mean basic ventilation rate in h^{-1}, was estimated from a pressurization test, giving 0,3 à 0,35 h^{-1}. That rather poor result, for a mechanically ventilated building, in spite of the excellent airtightness of walls and roofs, led to corrections on the window assembly. The coefficients $A_\circ$, A_1, A_2 and A_3 followed from a statistical analysis on all 12-hour mean data, using a transfer function technique (3).

Results

Calculations	Compactness C	1,19 m ($A_\circ$ = 358 m^2, V = 426 m^3)
	Mean $\bar{U}$-value	0,32 $W/(m^2K)$
	INSULATION LEVEL	K 29 ($K = 200\ \bar{U}/(1+C)$ (3)
Measurements	Regression coefficients	$A_\circ$ = 3,8 à 4 kWh/d
		$-A_1 \approx A_2$ = 3,5 à 3,7 kWh/d
		A_3 = -0,11 à -0,14 kWh/d

Combining equation (1) and (3) gives:

INSULATION LEVEL	K 29 à K 31

or, calculation and measurements agree very well.

The data also show a positive effect of solar gains on the energy use for heating. Nevertheless, θ_i seemed linked to θ_e and E_s. Or, part of the solar gain was wasted in a unnecessary rise of $\bar{\theta}_I$.

4. The energy use (5)

On January, the first, 1984, the prototype house was occupied by a young family with 2 children. From January to December 1984, their energy use, together with the inside and outside climatic conditions, were monitored in detail, while, during the first 4 months, the family also noted the time, each day, rooms, hot water and apparatus were used. This intensive, follow-up aimed a better understanding of the energy household in a highly insulated building, and of the inhabitants' influence. Also a comparison with the predicted energy demand was searched.

Results:

Predicted net energy use for heating

All calculations were performed with a one zone, steady state software package, called "VERBRUIK"(1). Parameters: the heating season mean inside temperature $\overline{\theta}_i$, the heating season mean ventilation rate $\overline{\beta}$, the heat recovery effectiveness. The last was taken into account by lowering $\overline{\beta}$ to an effective value $\overline{\beta}_{eff}$.

Extremes calculated:

$\overline{\theta}_i$ = 17°C — Q_n = 3170 kWh/Y

$\overline{\beta}$ = 0,5 h^{-1}, $\overline{\beta}_{eff}$ = 0,15 h^{-1} — Degree days: 880

$\overline{\theta}_i$ = 20°C — Q_n = 8400 kWh/Y

$\overline{\beta}$ = 0,9 h^{-1}, $\overline{\beta}_{eff}$ = 0,57 h^{-1} — Degree days: 1930

The internal gains Q_i (household, inhabitants) apports some 2370 to 3190 kWh/Y in the gross heating demand. The sun gives ~2150 kWh/Y net gains. The net effect of exhaust air heat recovery largely depends on the ventilation rate $\overline{\beta}$ and the efficiency of the unit. Compared to $\overline{\beta}$ = 0,5 h^{-1}, no heat recovery, the result was:

θ_i = 17°C, $\overline{\beta}_{eff}$ ≐ 0,15 h^{-1} — ΔQ_n = -1980 kWh/Y

θ_i = 20°C, $\overline{\beta}_{eff}$ = 0,57 h^{-1} — ΔQ_n = + 600 kWh/Y

Measured energy use

On a monthly and yearly basis (1984): TABLE 2.

MONTH	ELECTRICITY USE kWh	HEATING H kWh	HOUSEHOLD WARM WATER HH+WW kWh	$\overline{\theta}_e$ °C	$\overline{\theta}_i$ °C	SOLAR GAIN (51° NL) kWh
J	2361	1540	820	3,0	20,3	89,9
F	1890	1217	673	2,4	19,1	223,6
M	1576	953	623	4,0	18,1	346,2
A	993	453	540	8,1	19,1	656,2
M	589	90	500	10,6	19,5	436,8
J	437	0	437	14,3	19,5	654,8
J	296	0	296	16,7	21	649,9
A	448	0	448	18,3	21	604,7
S	472	92	<480>	13,8	20	308,6
O	726	166	<560>	11,8	19	281,3
N	903	303	<600>	8,8	18,5	170,1
D	1554	904	<650>	4,5	18,5	83,1
	12345 100%	5718 46%	6687 54%			4505,2

< >: until August 1984, the electricity use was logged each 15'. These plots made it easy to distinct between H and HH+WW. From September, only a global reading was available.

Table 2: energy use in the prototype house (1984)

Remarkable in the table:

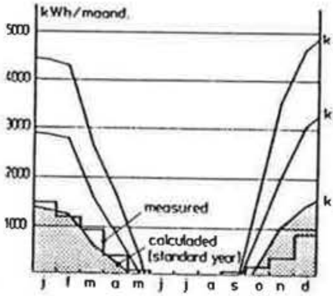

fig 8 heating demand k 30, compared to k 69 - k 104

- the low total energy use: half the mean value of, for Belgian standards, "normally" insulated, gass or oil fired K 70 to K 90 houses (~25000 kWh/Y) (fig. 8) or, the excellent insulation is reflected in a very high energy economy.
- the balance between H and HH+WW: in K 70-K 90 houses with direct electrical heating 70% - 30%, here 46% -54%

The results also agree well with the predictions: 5718 kWh/Y lays between 3170 kWh/Y and 8400 kWh/Y. Entering the measured energy use, the "VERBRUIK"-software generated as parameters:

$\overline{\theta}_i$ = 18°C, $\overline{\beta}_{eff}$ = 0,4 à 0,5 h^{-1}, Q_i ≈ 500 to 700 W.

That rather high $\overline{\beta}_{eff}$-value justified some doubts about the efficiency of the heat recovery unit.

On a weekly basis:

As statistical correlation between weekly electricity use, weekly mean temperature difference $\overline{\Theta}_i - \overline{\Theta}_e$, weekly mean south facing photovoltaic cell output $\overline{E}_s$ and weekly HH+WW energy use, we found ($r^2 = 0,962$):

$$Q_E = 26,9\ (\overline{\theta}_i - \overline{\theta}_e) - 4,7\ \overline{E}_s - 0,88\ Q_{HHUW} - 208,1\ (kWh/w)$$

This relation shows
- the positive influence of solar gains
- a less than 1 regression coefficient between Q_E and Q_{HHWW}, or, a higher energy use for HH + WW lowers the heating demand.

It also gives as temperature of no more heating: θ_e = 11 à 12°C. For K 70-K 90 houses, that value ranks 14-15°C, or, the better the insulation, the lower the number of degree days (see predicted results).

5. Summer conditions

Apart from calculated simulations (6), the summer situation in the prototype house was monitored in July-August 1984 (θ_i, θ_e, E_s), with variation of:
- curtains open (0), closed (1) (X4)
- inner doors open (0), closed (1) (X5)
- heat recovery unit on (1), off (0) (X6)
- different ventilation strategies (X7: 1, 2, 3, 4) (1: best, 4: worst)

A regression analysis on all data for the living room gave on a daily mean basis:

$$\theta_i = 7,9 + 0,4\Delta\theta_{ej,j-1} + 0,77\ \theta_{e,j-1} + 0,056\ E_{s,j} + 1,7\ X\ 4 +$$
$$1,6\ X\ 5 - 0,17\ X\ 6 + 0,85\ X\ 7 \quad (r^2 = 0,97)$$

with $\Delta\theta_{ej,j-1}$: outside temperature difference today-yesterday

$\theta_{e,j-1}$: outside temperature of yesterday

That correlation reveals a net positive influence of the curtains as solar device, a major relation with yesterday's ouside temperature and the difference today-yesterday and a positive influence of a higher ventilation rate without heat recovery (X7 = 1).

Also, the regression fitted very well with the calculated simulations. Both showed rather high inside temperatures during hot weather periods:

daily mean value $\overline{\theta}_i \approx 31°C$

daily peak $\theta_{i,M} \approx 35°C$

So, an effective solar device, a summer position on the mechanical ventilation, including continuously a $\beta = 2\ h^{-1}$ ventilation rate, air inlet north, bypassing the heat recovery, and a stony floor on the concrete slab in living room and kitchen became a must.

6. Conclusions

The major result of the work on the K 30, is the fulfilment of producing an energy efficient building system. Compared to a traditional K 70 - K 90 house, half the energy consumption is measured, with a higher bill for HH+WW than for heating. Through that, a search for further heating economics became of second order compared to improvements in the HH+WW energy use.

Nevertheless, during the work, some weak points appeared:
- the colour differences (dark ←→ light) between window + attic elements and outside wall
- the threshold construction
- a too high infiltration through the window frames
- the lack of solar devices
- no specific summer ventilation strategy
- a low inertia (only the concrete floorslab is an active storage surface), with, as a result, a restricted floor finish choice.
- the rather low efficiency of the heat recovery unit

Before commercialization, these weaknesses have been cured.

7. References

(1) Laboratory of building physics, K.U.-Leuven, Software-packages WAND, RESPONS, VERBRUIK , KOBRU 82

(2) Laboratory of building physics, K.U.-Leuven, Etap K 30 - system, part 1, Theoretical analysis of the thermal performances, 1984 (in Dutch)

(3) Laboratory of building physics, K.U.-Leuven, Etap K 30 - system, part 2, Measuring the thermal performances of the envelope, 1984 (in Dutch)

(4) Laboratory of building physics, K.U.-Leuven, Etap K 30 - system, part 3, Analysis of the physical properties and construction of the composing elements, 1984 (in Dutch)

(5) Laboratory of building physics, K.U.-Leuven, Etap K 30 - system, part 4, Energy consumption, 1985 (in Dutch)

(6) Laboratory of building physics, K.U.-Leuven, Etap K 30 - system, part 5, Summer situation, 1985 (in Dutch)

(7) Hens H., Wouters P., Boogaerts F., Study of a building system with low energy demand, technical report R-D Energy, Governments' office for scientific policy, 1985 (in Dutch)

(8) Batech n.v., Etap K 30, Ontwerp, analyse en optimalisatie, realisatie van een woning met laag energieverbruik, 1986