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COMPUTER SIMULATIONS FOR BUILDING LOADS AND INDOOR CLIMATE CALCULATIONS

Summary. Various approaches to the computation of indoor temperatures and/or the heating and cooling loads of occupied dwellings are presented. Unizone and multizone calculations are discussed. An overview of static and dynamic formulations is performed, with illustrative examples. The presentation is completed by some comments on available data for carrying building loads computations and on features of some computer programs developed at the Building Physics Laboratory.

I. INTRODUCTION

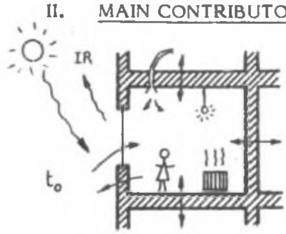
The establishment of a heat balance is necessary during the design process of new buildings in order to estimate their heating or cooling requirements in view of a proper choice of thermal equipments. Due to the growing impact of energy prices on the maintenance of dwellings, improvements of heating or cooling systems on existing buildings as well as of their insulation level are very frequently studied. Correct solutions also require a careful analysis of their heat budget.

For many years, such calculations had to be performed by hand. The building was generally considered as unizone or a only single sample part was selected and generally a static approach was used. In the early 1960's, procedures were introduced to take into account a certain inertia of the building (Carrier method for air-conditionned building design |18|). They however implied rather crude simplifications and were, for example, unable to predict seasonal overheating occuring from solar radiation loads.

The advent of computers, and in particular microcomputers, gives now the opportunity to perform refined analyses of buildings thermal behaviour. Unizone calculations remain interesting for their easy and rapid sizing of energy loads, but multizone methods are required when distinct parts of a building are sollicitated differently. In particular, they provide useful information on resulting temperatures in unheated parts of a dwelling, where heat is supplied only to specific rooms. Static studies are most suitable when an overall picture of the problem is desired, using time-averaged quantities as input data. Finally, dynamic computations will be performed when intermittent heating or cooling occurs with characteristic time periods inferior to 24 hours or when solar radiations variations are to be considered. In those latter cases, it is sometimes sufficient to come back to unizone representations of the building. Simplified models, using equivalent electrical networks are then developed. Those may be required if fast calculations on small computers are to be performed.

For instance, they represent the only possible simulation of a building that can be implemented on a micro-computer designed for the automatic control of an HVAC system regulation in real time.

II. MAIN CONTRIBUTORS TO A SENSIBLE HEAT BALANCE



The terms of a room heat balance inside a dwelling may be classified following their origin. Climatological conditions affect the heat budget, if the room presents a connection with the outdoor, through an external wall and a window for instance. Solar radiations load the room. This effect will depend on the period of the year considered, the cloud cover, the wall and window's orientation and areas, the building's location (i.e. latitude and longitude) and surroundings which could produce shadowing.

Fig. 1. Pictorial presentation of a room heat balance terms

Rys. 1. Obrazowe przedstawienie czynników uwzględnianych w bilansie cieplnym pomieszczenia

Furthermore, the external wall will experience long wave radiative heat exchanges with the sky cover, typically at a much lower temperature then its surface.

On the other hand, conductive heat exchanges will occur between the room and the outdoor environment and air infiltration, mainly through leaks of the window frame will modify the internal balance. This last contribution, unfortunately constitutes one of its least accurate terms.

Internal exchanges will also occur with the nearby rooms. They mainly happen by conduction through inside walls and structures but convective exchanges, for instance by air movements through doorways, may represent significant contributions. They are however seldom considered.

Internal loads are twofold. First heating and cooling systems terminal units such as radiators or air outlets for mechanical ventilation provide generally well defined heat fluxes, except if their heating or cooling powers constitute the unknowns of the problem. Second, so-called free gains are to be taken into account. They consist namely of heat provided by the presence of occupants (often treated as purely convective), domestic appliances, work equipments such as computer terminals or workshop machines.

Heat loads produced by lightings are to be considered in that category. Their contribution is relatively complex, partly convective, partly radiative, depending on their type and location. In air-conditioned offices, they are often mounted in ceilings and used as air extraction outlets. Their effect on the heat balance is therefore greatly reduced to the expense of the return air plenum budget.

Simulations may be led in two different directions which in fact differ only by the inversion of a matrix. During the design process of a building or the study of improvements to its envelope for example, one will assume that prescribed set-point temperatures should be respected in all zones and compute the heat requirements or extraction rates necessary to respect those constraints. On the other hand, in order to verify the adequacy of chosen heating and cooling powers in all zones, one will compute the resulting indoor temperatures.

This calculation is particularly important for intermittent heating, in order to predict the necessary preheating period before comfort conditions are satisfied. It is also very helpful for the determination of risks of overheating by direct solar radiations in very exposed areas in hot summer conditions.

Finally, a third situation may occur, when multizone calculations are available. If some

parts of the dwelling are likely to be heated or cooled, it should be possible to compute powers required to satisfy set-point temperatures in those rooms, while determining the free floating temperatures in the remaining part of the building.

As a conclusion, we may summarize hereunder the information needed to perform building loads calculations :

- the geometry, location and orientation of the building;
- a minimum knowledge of its site and of the possibilities of shadowing by its surroundings;
- exterior and interior walls thermal parameters (thickness and thermal conductivity of all layers constituting the walls, to which their density and heat capacity should be added if dynamic calculations are to be performed);
- all free gains likely to be experienced (amounts and schedules);
- eventually, the schedule of operation of the heating and/or cooling systems;
- meteorological data consisting of at least the outside temperature, the global solar radiations experienced by a horizontal surface and the sunshine period (or cloud cover) during the period considered.

III. GENERAL ASSUMPTIONS

Building loads calculations generally assume a set of approximations which will be here briefly overviewed.

The material properties remain unchanged with time or temperature. This hypothesis is very reasonable as long as very important changes do not occur in the walls, as it is the case for usual dwellings. Some computer programs, using for instance finite difference techniques to solve the unsteady Fourrier equation for heat conduction through structures allow time variations of the conductivities, density and specific heat. This phenomenon may happen for example if a wall is wetted by a sudden rain, but would yield minor changes. The dependence of thermal properties with temperature is more important for specific situations (i.e. furnace walls) but only in applications not directly relevant to buildings loads calculations.

Zones are considered at an homogeneous uniform temperature. They are characterized by a single node at a reference temperature in the calculation. Air movements are thus neglected, as well as any temperature stratification inside the rooms. This may affect the overall heat balance by introducing uncertainties on the actual convective exchanges along walls surfaces and on the true temperature at which quantities of extracted air leave the room. However, some procedures take into account the air capacity and the delay it may bring to the response to a sollicitation. This is sometimes performed by semi-empirical corrections, strongly dependent on experimental observations.

Zones may be defined in a very general way and do not have to be bounded by true physical boundaries. In large spaces, where significant spatial temperature differences are expected, partioning may be performed. Zones will be linked in that case by artificial boundaries, through which convective exchanges should be allowed. They are often simulated by fictitious purely resistive walls, whose heat transfer coefficients are difficult to ascertain. Parametric studies on a specific case have shown however that the choice of such coefficients has not a very sensitive effect on the overall results |17|.

Conductive heat flows through the walls are treated as one-dimensional. Actual complex structures, such as floor beams or composite walls would indeed require two - or three- dimensional calculations. Those would demand very sophisticated and time consuming local solutions, whose accuracy would reveal absolutely unrelevant with the overall accuracy of the problem. Those walls are thus simulated by equivalent multilayered structures in terms of overall thermal resistance and capacity. The main defect of this approach resides in the ignorance of thermal bridges occuring in corners and at the junction between two structures, for instance along window frames. It may lead to a few percents of unaccuracy in those locations.

The air infiltration air contribution is generally rather crudely estimated. It is difficult to assess the exact flow rate entering each room. In many cases, infiltration occurs mainly in the ground floor and air is distributed to other levels through lift-and staircases. Computer programs often assess prescibed flowrates to each room in connection with the outside, assuming air entering at the outdoor temperature. More refined calculations would require the knowledge of the pressure field around the building, which depends on many factors such as wind intensity and direction, nearby shields, etc, ... which are seldom available in practice.

IV. COMMON FEATURES

The following procedures should not be considered as general to all building loads computer programs. They are widely used and in particular in programs developed in the Building Physics Laboratory.

IV.1. Internal heat exchanges

The internal surfaces of walls are submitted to both radiative exchanges with other walls and convective exchanges with the nearly air layers. It is a common use to globalize those effects and define a resultant temperature of the room, t_R, which may be interpreted as the temperature recorded by a globe thermometer located in the center of the room. It is defined as :

$$t_R = \frac{h_c t_a + h_r t_r}{h_c + h_r} \qquad (C) \qquad (1)$$

t_a represents the air temperature in the room and t_r stands for a reference radiative temperature. The convective exchange coefficient h_c is obtained from well known non-dimensionnal laws between the Nusselt and Reynolds or Grashof numbers. The radiative exchange coefficient h_r is deduced from the linearization of Stefan's law :

$$h_r = 4\,\varepsilon\,\sigma\,T_m^3 \qquad (W/m^2\,K) \qquad (2)$$

where :
- T_m represents the mean radiant temperature of the room (K)
- ε stands for the emissivity of the surface
- σ is Stefan's constant ($5.7\ 10^{-8}$ $W/m^2\,K^4$).

Globalized heat exchanges are then characterized by a unique coefficient :

$$h = h_c + h_r \qquad (W/m^2\,K) \qquad (3)$$

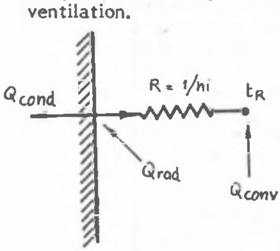
A further simplification assumes the equality of resultant and air temperatures outdoor. An external global exchange coefficient h_o may thus be defined also.

Typical values are :

indoors : $h_i = 8$ $W/m^2\,K$
outdoors : $h_o = 23$ $W/m^2\,K$

They correspond to inside natural convection and outside forced convection with a characteristic wind velocity of 4m/s along the wall. Indoor conditions considered are $t_R = \pm 20$ C and $\varepsilon = 0.9$.

Those approximations are very reasonable for the range of temperatures and convection effects occuring indoors. Experience also shows that the use of a resultant temperature is very satisfactory to calculate heat fluxes created by mechanical ventilation.



Radiative and convective contributions remain however separated in the calculation of the heat balance of the internal surface of a wall, as pictured on figure 2. Convective heat fluxes (for instance issued from internal free gains such as ventilation) are directly applied to the center node of the room, while radiative fluxes are distributed on the surfaces of internal walls. In dynamic calculations, they are explicitely taken into account (by specific response factors, for example).

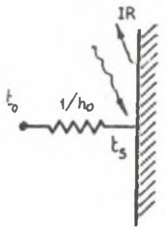
Fig. 2. Heat balance of the internal surface of the wall
Rys. 2. Bilans cieplny wewnętrznej powierzchni ściany

In static approaches, only central nodes are considered. The radiative flux impinging on a surface is then partly distributed by conduction to the neighbouring zone, partly loads the room's central node ($Q_{rad, room}$) :

$$Q_{rad, room} = \frac{h_i}{U + h_i} Q_{rad} \qquad (W) \qquad (4)$$

Where U stands for the global transfer coefficient of the wall (W/m^2 K).

IV.2. The "sol-air" temperature



It is also a common use to merge all sollicitations of an external surface into a unique term, by defining an equivalent "sol-air" temperature t_o^*. The heat balance of this surface (at temperature t_s) results from exchange with the air at temperature t_o, solar radiation and infrared losses to the sky cover. It is possible, without approximation to represent it by an overall exchange with the ambiance at a modified temperature :

$$h_o (t_o - t_s) + \alpha I_G - \varepsilon R = h_o (t_o^* - t_s) \qquad (W/m^2) \qquad (5)$$

Fig. 3. Factors contributing to the heat balance of the wall external surface

Rys. 3. Czynniki uwzględniane w bilansie cieplnym zewnętrznej powierzchni ściany

In equation (5), I_G represents the global solar radiation received by the surface, and α, its absorption coefficient. R stands for the infrared losses experienced by a black surface with same orientation, and ε for the emissivity of the wall.

The procedure should be modified for windows, which transmit directly part of the solar radiation and absorb part of it, expecially if they are equipped with solar protections. From that absorbed part, a certain amount is later transmitted to the room. To take into account those phenomena, a "solar factor" S if often used to characterize the window, in place of α in equation (5). It is defined as the ratio between the actually transmitted radiation and the total solar radiation received on its external surface.

V. METEOROLOGICAL DATA

Meteorological stations record different data. Most of them provide only outdoor temperatures and some information on the weather status, for instance, rain level and sky clearness or cloud cover. Some, better equipped, are able to perform solar radiations measurements, generally recording the global radiations received by an horizontal surface.

National Institutes of Meteorology provide much more complete information. They are able to record separately the global solar radiations and the beam component received by a surface always oriented perpendicularly to the solar ray. A crucial problem resides nowadays in the standardization of equipments used throughout the world as the recordings seem to be quite sensitive to the frequency range of the instrumentation.

On the other hand, the monitoring of buildings by University departments or technical teams usually include global solar radiations measurements only.

An horizontal surface receives a global solar radiation I_{GH} (W/m^2). It results from the combination of two components :

$$I_{GH} = I_{DH} + I_{BH} \qquad (W/m^2) \qquad (6)$$

where · I_{BH} is the beam component (I_{BH} is seldom recorded. It has generally to be deduced from the beam radiation collected on a rotating plane which stays perpendicular to the solar rays) and I_{DH}, the diffuse contribution, resulting from diffraction, absorption and re-emission of solar rays in the atmosphere. Commonly, it is assumed isotropic.

Any tilted surface receives diffuse radiations, part of it resulting from the reflection of solar radiations on the ground.

It also receives beam radiations when it is directly exposed to solar rays. In terms of energy loads for buildings heat balance calculations, the pretreatment of meteorological data consists in determining the total solar radiations received by all surfaces of the building.

If only I_{GH} is available, correlation laws are to be applied to determine its components. The most used is Liu and Jordan law. It was developed on daily averaged data recorded in the United States of America but proved to remain satisfactory in other parts of the world, even when predicting hourly values. However, it has been corrected for Belgian data by Laret, using 25 years of recordings :

$$I_{DH} / I_{GH} = 1 - 1.63\,(J - 0.11)^2 + 0.77\,(J - 0.11)^3 \qquad \text{if } J > 0.11$$

$$I_{DH} / I_{GH} = 1 \qquad \text{if } J < 0.11 \qquad (7\text{ a - b})$$

In this relationship, J represents the global horizontal radiation, normalized to its maximum, obtained in clear sky conditions :

$$J = I_{GH} / I_{GH\,CS} \qquad (8)$$

This latter value may be known analytically. Indeed, it may be considered as a fraction of the extraterrestrial radiation that the horizontal surface would receive in the absence of atmospheric absorption and diffraction :

$$I_{GH\,CS} / I_{GH\,EX} = k \qquad (9)$$

The coefficient k results from the absorption effect of the atmosphere, depending on the latitude of the site and from the level of pollution of the air. In Belgium, it may be set to 0.7. The extraterrestrial radiation was experimentally determined :

$$I_{GH\,EX} = [\,1353 + 45\,.\,326 \cos(2\pi j/365)\,] \cos\theta_H \qquad (10)$$

where j stands for the rank of the day considered in the year and θ_H is the incidence angle of solar rays on the ground :

$$\theta_H = \cos^{-1}[\,\sin\delta\,.\,\sin\phi + \cos\delta\,.\,\cos\phi\,.\,\cos\omega\,] \qquad (11)$$

where ϕ is the latitude, ω the solar time (in angular units) and δ the solar declination, given by :

$$\delta = 0.40928 \sin|\,(2\pi/365)\,(284+j)\,| \qquad (12)$$

The solar time is deduced from the local official time, using :

$$\omega = t - 12 + TZ + EH - \varepsilon - \lambda \qquad \text{(hours)} \qquad (13)$$

where t is the official time, TZ stands for the time zone with respect to Greenwich reference, ε is an eventual correction for seasonal changes (i.e. summer time), λ is the longitude of the site and :

$$ET = 0.0072 \cos\alpha - 0.0528 \cos 2\alpha - 0.0012 \cos 3\alpha - 0.1229 \sin\alpha - 0.1565 \sin 2\alpha - 0.0041 \cos 3\alpha \qquad (14)$$

with $\alpha = 2\pi j/365$

Consequently, a tilted surface receives :

$$I_G = I_B + (I_D + I_R) \qquad (W/m^2) \qquad (15)$$

where, if s represents the slope of the surface and θ, the solar incidence on this surface :

$$I_D = (1+\cos s/2)\, I_{DH} \qquad (16)$$

$$I_B = (\cos\theta / \cos\theta_H)\, I_{BM} \qquad (17)$$

and the radiation issued from reflection of solar beams on the ground :

$$I_R = \rho \left(\frac{1-\cos s}{2}\right) I_{GH} \qquad (18)$$

where ρ is called the ground albedo, equal to 0.2 in normal conditions but reaching values close to 1 for water surfaces or a snow cover.

Suitable meteorological data have to be selected for building loads analysis. It is indeed impossible to run computational programs in all imaginable climatic conditions. Selection procedures may vary from country to country. In Belgium, typical periods have been determined and calculations are mostly performed on some of them.

From 25 years of bi-hourly recordings, three typical years were defined. They consist of a warm, a cold and a mean year. The latter one is most often considered. It consists of twelve actual months which, however, did not appear in sequence in the reality and were chosen as the closest to the average behaviour of the climate in this country. When using this data, it is advised to perform additional computations on selected extreme periods, very cold weather to test the buildings performance in very drastic winter periods and a very sunny period to determine risks of overheating in largely glazed dwellings in summer or mid-seasons.

A shorter data set has also been deduced from those 25 years of recordings. It consists of sets of 3 days, each characterizing a specific day, with different levels of sunshine periods : one day of cloudy sky, one of almost clear sky and one in between. This "36-days year" is particularly suitable for static calculations on daily averaged values. It may be used with dynamic computations if cyclings on each day are performed in order to sollicitate the building's thermal inertia correctly. However, this data smoothes out the high frequency changes of solar radiations and will not predict correct overheating risks.

A last word should be mentioned about long wave exchanges of the building with the surroundings. This term is seldom recorded and crude correlations are usually used. It is known that an horizontal black surface will loose a maximum heat of 100 W/m^2 to the sky cover, by clear sky. Any cloud cover will decrease that amount. The infrared losses are commonly linked to the sunshine ratio S/SO, between the day's duration of sunshine and the length of that day, and to the slope (s) of the surface :

$$R = 100\,(5/6\ S/SO + 1/6)\left(\frac{1+\cos s}{2}\right) \qquad (W/m^2) \qquad (19)$$

The quantity R is expressed for a black surface. The actual loss will be ε R, where ε is the emissivity of the wall considered, as expressed in (5). This relationship becomes effectively obsolete during the night. There, the infrared losses are assumed to remain at the level of the previous day or to change linearly until the next morning.

VI. STATIC MULTIZONE CALCULATIONS

Having recognized all contributions of a room's heat balance, we are now able to express it mathematically. We shall first overview the static approach. The index "i" will refer to the room considered.

Among the heat gains, we may gather :

- the heat produced by the heating equipments : Q_i
- the free gains to the room : Q_{ii}
- the solar gains by transmission through the windows of surface A_{iw} : $S_i\, I_{Gi}\, A_{iw}$
- the gains from solar radiations on opaque external walls. Those are however included in the general term of exchanges with the outdoor environment.

Among heat losses, we observe :

- the losses towards outdoor through the external walls (area A_{io}) :

$$A_{io}\, U_{io}\, (t_i - t_o^*)$$

where t_o^* stands for the "sol-air" temperature

- the convective exchanges with adjacent rooms :

$$A_{ij}\, U_{ij}\, (t_i - t_j)$$

In both those terms, t_i stands for the room's resultant temperature and U for the global heat transfer coefficient defined by :

$$1/U = 1/h_o + \sum_m e_m/k_m + 1/h_i \qquad (19)$$

where h_o represents the external global exchange coefficient in the case of an outside wall or the internal coefficient to be accounted for in the adjacent room considered. e_m and k_m are respectively the thicknesses (m) and thermal conductivities (W/m C) of all layers constituting the wall.

Finally, the heat losses by infiltration of air :

$$\rho\, C_p\, \dot{V}\, (t_i - t_o)$$

where ρ stands for the specific mass of air (1.29 kg/m^3 at atmospheric pressure and 30 C) and C_p for the specific heat (1.006 kJ/kg K). $\dot{V}$ represents its volumic flow rate (m^3/s).

For each room, it is thus possible to write :

$$Q_i + Q_{i,i} + S_i\, I_{Gi}\, A_{iw} = \sum_j A_{ij}\, U_{ij}\, (t_i - t_j) + A_{io}\, U_{io}\, (t_i - t_o^*) + \rho\, C_p\, \dot{V}\, (t_i - t_o) \qquad (20)$$

The distinction between heat gains and losses is evidently purely arbitrary. Cooling loads produced by mechanical ventilation, for example, will yield negative Q_i's, while conductive exchanges with warmer nearby rooms will result into heat gains for the room.

In the form of equation (20), radiative gains are treated as convective loads. The correction mentioned in § IV.1. and illustrated by equation (4) has to be applied.

Equation (20) being repeated on each room, a system of linear algebraic equations takes the following matricial form :

$$\underline{\underline{A}}\, \underline{T} = \underline{Q} + \underline{D} \qquad (21)$$

where $\underline{T}$ is the vector of room temperatures and $\underline{Q}$ the heating or cooling loads. Matrix $\underline{\underline{A}}$ is often called the structural matrix. Its terms include walls areas, transfer coefficients and infiltration rates. All remaining (known) terms are gathered in vector $\underline{D}$.

If heating and cooling loads are known, the computation will produce the resulting resultant temperature field in the dwelling :

$$\underline{T} = \underline{\underline{A}}^{-1}\, (\underline{Q} + \underline{D}) \qquad (22)$$

On the other hand, if all rooms should be maintained at prescribed set-point temperatures, equation (20) will directly produce the necessary heating and cooling loads :

$$\underline{Q} = \underline{\underline{A}}\, \underline{T} - \underline{D} \qquad (23)$$

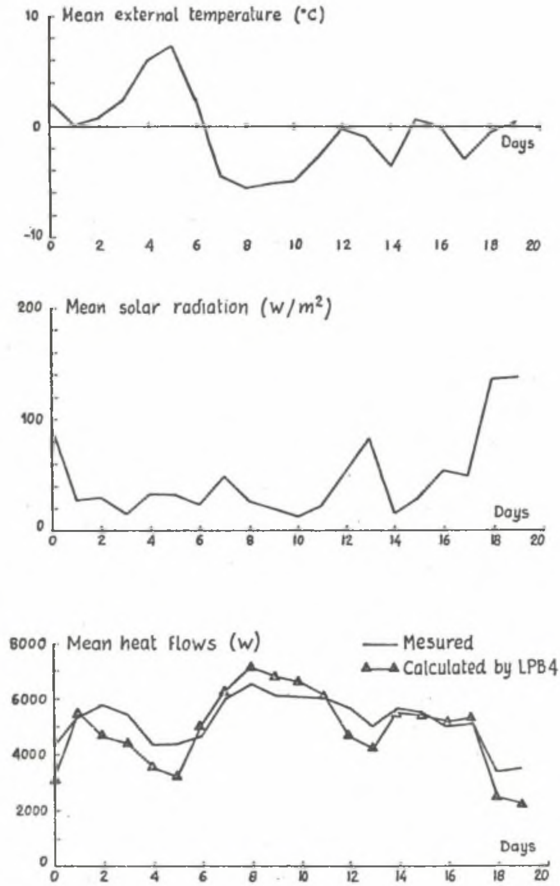


Fig. 4a,b,c. Examples of heat loads calculations - comparison of daily averaged heat flows with experimental data

Rys. 4a,b,c. Przykładowe obliczenia obciążeń cieplnych - porównanie uśrednionych dziennych przepływów ciepła z danymi eksperymentami

However, in most cases, only selected rooms are heated. Let n be the number of zones constituting the dwelling and let us suppose m rooms only are equipped with heating devices (m < n). We shall compute the required heating powers for respecting set-points in those m rooms, while it would be interesting to know the influence of such selective heating on the remaining (n - m) rooms. It is possible to isolate subvectors $\underline{T}_1$ and $\underline{Q}_1$ of m components and $\underline{T}_2$ and $\underline{Q}_2$ of (n - m) components and re-organize equation (21) as :

$$\begin{bmatrix} \underline{\underline{A}}_1 & \underline{\underline{A}}_2 \\ \underline{\underline{A}}_3 & \underline{\underline{A}}_4 \end{bmatrix} \begin{bmatrix} \underline{T}_1 \\ \underline{T}_2 \end{bmatrix} = \begin{bmatrix} \underline{Q}_1 \\ \underline{Q}_2 \end{bmatrix} \quad \begin{bmatrix} \underline{D}_1 \\ \underline{D}_2 \end{bmatrix} \tag{24}$$

and solve those subsystems by means of the Frobenius-Schur procedure for Q_1 and T_2 :

$$\underline{Q}_1 = (\underline{\underline{A}}_1 - \underline{\underline{A}}_2 \underline{\underline{A}}_4^{-1} \underline{\underline{A}}_3) \underline{T}_1 + \underline{\underline{A}}_2 \underline{\underline{A}}_4^{-1} \underline{D}_2 - \underline{D}_1 \tag{25}$$

$$\underline{T}_2 = \underline{\underline{A}}_4^{-1} (\underline{D}_2 - \underline{\underline{A}}_3 \underline{T}_1) \tag{26}$$

An example of heat loads calculations is presented on figures 4.a. through 4.c. Daily averaged heat flows are compared with experimental data. The agreement between the two curves could have been improved if actual infiltration rates would have been less crudely estimated. Moreover, measurements were performed on a recently built family house, before indoor finishing tasks were performed. In particular, doors were absent and significant convective couplings have most probably occured, that were not taken into account.

VII. STATIC UNIZONE CALCULATIONS

In cases where the building is represented by a single zone, the set of equations (21) is reduced to a very simple expression :

$$Q_i + Q_{i,i} + K\, R_c\, I_{GH}/I_{GHCS} = K\,(t_i - t_o) \tag{27}$$

where K is an overall heat loss coefficient including conductive losses through the external walls and the effect of air infiltrations i.e. :

$$K = \sum_i A_i U_i + \rho\, C_p\, \dot{V} \tag{28}$$

The coefficient R_c is called the recuperation coefficient of solar radiations, characteristic of the building. For each wall, such a recuperation coefficient may be defined as :

$$R_{ci} = (1/h_o)\,(\alpha\, I_{GCS} - \varepsilon\, R_{CS}) \tag{29}$$

where I_{GCS} stands for the global solar radiations received by the surface, by clear sky and R_{CS} the loss by infrared exchange in the same conditions.

For a window, we may define :

$$R_{ci} = (S/U)\, I_{GCS} - (1/h_o)\,\varepsilon\, R_{CS} \tag{30}$$

The overall recuperation is than provided by :

$$R_C = \frac{\sum_i (AU)_i\, R_{ci}}{K} \tag{31}$$

This definition, as well as its use in (27) implies that :

$$I_G/I_{GCS} = R_C/R_{CS} = I_{GH}/I_{GHCS} \tag{32}$$

for any surface. This assumption generally overestimates the total solar gain of the building, especially on the southern orientation (but underestimates it on a north orientation).

Equation (27) is commonly used in the shorter form :

$$Q_i = K\,(t_{NH} - t_{WH}) \tag{33}$$

defining a temperature "without heating" :

$$t_{WH} = t_o + R_C\,(I_{GH}/I_{GHCS}) \tag{34}$$

It is the temperature naturally experienced by the building in the absence of occupancy and heat load. t_{NH} is called a temperature of "no heating" and defined by :

$$t_{NH} = t_i - Q_{i,i}/K \tag{35}$$

When the indoor temperature reaches t_{NH}, the heat produced by occupancy will be sufficient to respect the set point temperature, without need of further energy consuming heat.

Those various definitions are illustrated on figure 5.

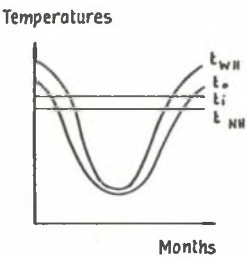
From (33), it is straightforward to calculate the energy demand of the building on a period :

$$E = \int_0^{\tau} Q\, d\tau = \int_0^{\tau} K\,(t_{NH} - t_{WH})\, d\tau \tag{36}$$

On the various days considered, a discretized form of (36) consists of :

$$E \simeq K \sum_0^{\tau} (t_{NH} - t_{WH})\, \Delta\tau \tag{37}$$

where K is assumed constant during the period and the sum covers only positive values of $(t_{NH} - t_{WH})$. With the use of standard meteorological data, equation (37) yields tables of "equivalent degree-days", which differ from classical degree-days by the fact that the equivalent temperatures t_{WH} are used instead of the outdoor air temperature t_o.



Equivalent degree-days tables provide the energy demand in function of various values of t_{NH} and R_{CCS}. They are constituted for prescribed periods (i.e. month by month or on a whole year) and for various values of the ratio R_C/R_{CCS}.

The present method proves very satisfactory for calculations of heat demands over long periods, at least superior to 10 days. This limitation results from the smoothing out of high frequency variations by the very simple representation of the building.

Fig. 5. Various temperature definitions

Rys. 5. Różne definicje temperatur

VIII. DYNAMIC MULTIZONE COMPUTATIONS

Static calculations do not consider the ability of the building structures to store thermal energy to eventually render it to the indoor volume after some delay. This effect of inertia is used when intermittent heating occurs, in order to maintain the indoor temperatures within a certain range, but with a minimal energy production. Moreover, it maintains a sufficient temperature level during nights or unoccupancy periods at a minimum cost. On the other hand, inertia will bring a certain delay to the establishment of set-point temperatures at the start-up of the heaters. Those phenomena should be taken into account at the stage of design and choice of the adequate heating system.

A comparison between hourly static and dynamic multizone computations on a large air-conditioned administrative building is presented on figures 6 a and b. Floating temperatures in the absence of cooling and required cooling loads for the satisfaction of set-point temperatures are pictured. Discrepancies occur mainly in the computation of temperatures and it could be shown that static predictions are extremely sensitive to the outdoor climate variations, essentially solar radiations. It should be noted also that a very accurate knowledge of the actual level of inertia of the structures seems unnecessary.

This advantage was confirmed on many examples and may be important as the heat capacity of some materials is sometimes difficult to find in the literature.

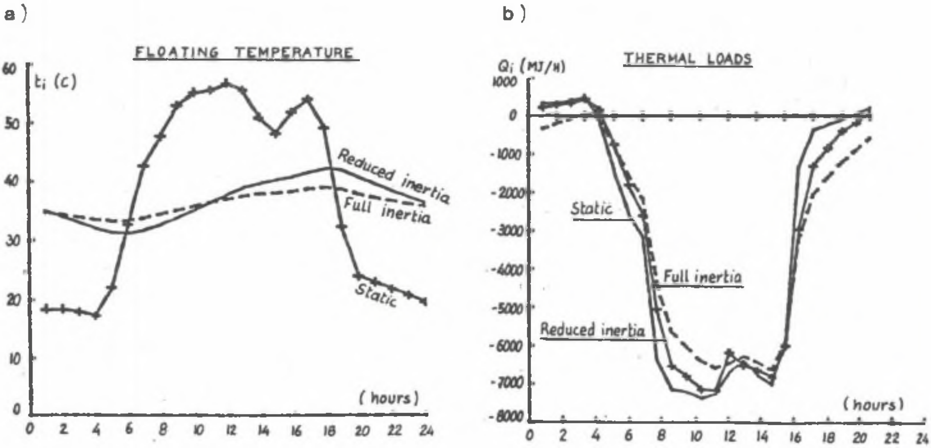


Fig. 6a,b. Comparison between hourly static and dynamic multizone computations on a large air-conditioned administrative building

Rys. 6a,b. Porównanie między godzinowymi, statycznymi i dynamicznymi obliczeniami dla dużego, klimatyzowanego budynku administracyjnego

VIII.1. The Fourier heat transfer equation

The general procedure followed by dynamic computations consists, like for steady state approaches, in expressing a general heat balance on each zone considered, where all contributions listed in § VI will appear. However, conductive heat transfers will be described now by the solution of the unsteady one-dimensional Fourier's equation and loads will become boundary conditions for that equation.

Any layer of material, when submitted to a difference of temperature between its surface experiences a heat flux q which may be expressed by the basic definition of Fourier :

$$q = -k \frac{\partial T}{\partial x} \tag{38}$$

This equation is valid at any location of a layer of thermal conductivity k (W/m K), x being the coordinate perpendicular to its surfaces. Conservation of energy on an elementary sublayer of thickness $\Delta x \rightarrow 0$ yields :

$$\rho C_p \frac{\partial T}{\partial t} = -\frac{\partial q}{\partial x} \tag{39}$$

where ρ and C_p stand respectively for the specific mass (kg/m^3) and heat capacity (J/kg K) of the material.

Equations (38) and (39) may be combined :

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} + \frac{\partial k}{\partial x}\frac{\partial T}{\partial x} \tag{40}$$

For thermal calculations of buildings, it is reasonable to consider that structures are constituted of multiple layers of different materials with piecewise constant conductivities. Consequently, equation (40) reduces to :

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \tag{41}$$

where $\alpha = \frac{k}{\rho C_p}$ is called the thermal diffusivity of the material (m^2/s).

At the present stage, it may still vary with time.

In order to obtain a complete and well posed mathematical problem, boundary conditions should be added to equation (41), together with the knowledge of the initial state of the layer. Required conditions are :

- the heat flux or the temperature on both surfaces (or both combined);
- the initial temperature throughout the slab.

Actual walls are generally constituted of multiple layers of different materials. Equation (41) applies to each of them. They will be interconnected by continuity conditions on the temperatures of both sides of the interfaces. This remains a slight approximation but which is consistant with the one-dimensional modelization of the wall.

An analytical solution of (41) on a multilayered slab with adequate boundary conditions is impossible. It has to be solved by numerical techniques, for instance using the Crank-Nicholson scheme in finite differences :

$$T_i^{m+1} - T_i^{m} = \frac{\alpha \Delta t}{\Delta x^2}\left[\theta\left(T_{i+1}^{m+1} + T_{i-1}^{m+1} - 2T_i^{m+1}\right) + (1-\theta)\left(T_{i+1}^{m} + T_{i-1}^{m} - 2T_i^{m}\right)\right] \quad (42)$$

where $t = m\,\Delta t$ and $x = i\,\Delta x$

This procedure is unconditionally stable and second order accurate if θ is to be chosen as :

$$\theta = \frac{1}{2} + O(\Delta x, \Delta t) \quad (43)$$

where $O(\Delta x)$ represents a correction of the order of magnitude of Δx.

Continuity conditions should be expressed through local heat balances on elementary slices including the interfaces, in order to remain second order accurate.

The present method leads to the expression of a large system of algebraic equations that can be solved using fast algorithms suitable for the inversion of three-diagonal matrices. It remains however very heavy to use, due to the very large amount of calculations to be performed at each time step and repeated for each wall of the dwelling. Furthermore it requires the calculation of the temperature field in all locations inside the walls, while only surface temperatures and heat fluxes are needed to express the heat balance of the building. For this reason, other methods were developed that produced only the necessary information in the form of responses of the various structures to a limited set of elementary sollicitations to be later combined by superposition using the convolution principle. This approach, however, implies a complete linearity of the problem and in particular, that the diffusivities α remain constant with time.

VIII.2. Response factors

Let us consider any multilayered wall with associated air nodes on each side (figure 7). Let T_i represent the resultant temperature of the air side in the room considered and h_i the global exchange coefficient along the wall's internal surface (W/m^2 K). If the wall is in connection with the outdoor ambiance, T_o stands for the outside air temperature and h_o is the outdoor global exchange coefficient. If the wall is internal T_o is the resultant temperature of the adjacent room and h_o remains an internal exchange coefficient.

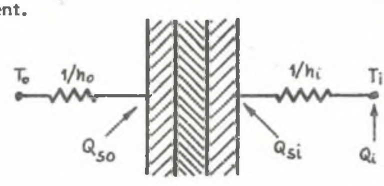


Fig. 7. Multilayered wall with associated air nodes on each side

Rys. 7. Wielowarstwowa ściana z węzłami po obu stronach

Any change of the internal temperature T_i will result from the combination of variations of :

- the outside temperature T_o;
- radiative fluxes Q_{so} received by the outside surface of the wall;
- radiative fluxes Q_{si} received by its internal surface;
- convective heat fluxes Q_i loading the inside air layer associated to the wall.

In the case of an external wall, Q_{so} will represent the solar radiations impinging on the surface and the infrared losses to the sky cover. Q_{si} (and Q_{so} for an internal room) are issued from the total radiative loads of the rooms, which are redistributed among their various walls. This redistribution may be performed in various manners. We propose here the features of our program LPB-1.

The first option consists of distributing all radiative heat loads with walls areas as weighting factors. A second option consists in distributing internal loads (from lightings, heat sources, ...) with respect to the walls areas and internal emissivities and solar radiations transmitted to the rooms with respect to the walls surfaces and absorption coefficients. This latter procedure does not respect the global energy conservation but implicitely allows some retransmission of solar radiations through the windows towards outside.

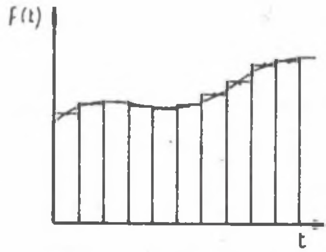


Fig. 8. Continuous function of time as a set of averaged quantities on constant time intervals

Rys. 8. Przedstawienie ciągłej funkcji czasu jako zbioru wielkości uśrednionych dla stałych przedziałów czasowych

All the abovementioned sollicitations are indeed very complex continuous functions of time, but they are generally available as sets of averaged quantities on prescribed constant time intervals, generally periods of 1 hour (figure 8). They may be considered as discrete distributions defined at each center of the time intervals and represented mathematically as :

$$f(t) = \sum_{n=1}^{\infty} f(n\Delta t)\,\gamma(t - n\Delta t) \tag{44}$$

where conventionnally, we have shifted the values of the discrete distribution at the right limit of the intervals of time Δt . γ (t) represents here a unit step function defined on the time interval Δt (rectangle).

The response in internal temperature at time $t = n\ \Delta t$ will depend not only on f(t) but also on all values taken by this function at times preceding $t = n\ \Delta t$. It will also appear as a discrete distribution of the form :

$$T_i(n\Delta t) = \sum_{k=1}^{\infty} f[(n-k)\Delta t]\,\gamma[t - n\Delta t]\,g(n\Delta t) \tag{45}$$

The coefficients g (n Δ t) are called the "response factors" in internal temperature of the structure when submitted to the sollicitation f(t).

Now, if the structure is sollicitated by the very particular function :

$$\begin{cases} f(t) = 0 & \forall t \neq \Delta t \\ f(\Delta t) = 1. \end{cases} \tag{46}$$

equation (45) reduces to :

$$q(n\Delta t) = T_i(n\Delta t) \tag{47}$$

Consequently, if we compute the response in internal temperature to a unit step function maintained on the basic time interval Δ t, as shown on fibure 9a, we shall obtain the whole set of response factors relevant to that sollicitation. By using (45) and applying the superposition principle, we determine the actual response to any sollicitation.

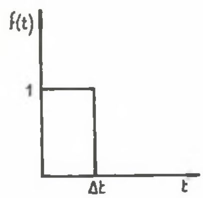


Fig. 9a. Unit step function maintained on the basic time interval Δt

Rys. 9a. Funkcja o wartości jednostkowej, stała dla podstawowego przedziału czasu Δt

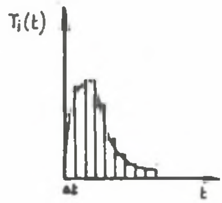


Fig. 9b. The response in internal temperature Ti(t) as a discrete distribution

Rys. 9b. Funkcja odpowiedzi temperatury wewnętrznej Ti(t) jako rozkład dyskretny

The principle of the present procedure is in fact linked to the convolution theorem, defined in the frame of Laplace and more particularly Z - transforms. The fact that we express responses in terms of internal resultant temperatures implies that global exchange coefficients should remain constant troughout the period considered for building loads calculations.

The technique of calculation is then based on the solution of equation (41) for unit step variations on the time base Δ t (= 1 hour generally) of the four typical sollicitations recognized hereabove. Those solutions are obtained by finite differences, using equation (42) with a typical time step much smaller than the time base (± 3 minutes). Responses are then averaged on the time base and provide 4 sets of response factors completely representing the wall's thermal behaviour. They are thus to be computed

STRUCTURE N°11 : Double brick with plasterboard panelling

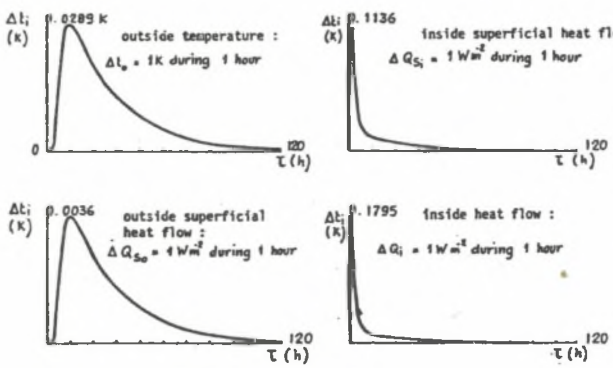


Fig. 10. Examples of response factors in the program LPB-1

Rys. 10. Przykładowe "współczynniki odpowiedzi" używane w programie LPB-1 only once and introduced in the building's heat balance through combinations based on (45). Figure presents an illustration of responses in internal temperature to the 4 elementary sollicitations.

The procedure presented here differs somehow from usual calculations of response factors. They are more genrally defined in terms of heat fluxes at surfaces of walls and computed by triangular discretizations of the actual sollicitations. From that point of view, those are not exactly coherent with the form of available data, especially information provided by experiments or meteorological stations.

Solutions are often obtained by use of Laplace or Z transforms, which allow analytical treatments. The combination of response factors with the intensities of the sollicitations is produced by convolution, which takes a particularly easy form in the transformed planes. Numerical calculation of the inverse transforms is necessary and results in a very careful search of poles of complex functions.

VIII.3. Dynamic heat balance

For any wall "l" of room "i", it is now possible to express the increments in internal temperature due to the four types of sollicitations. Capital letters are hereunder abandoned as temperatures are expressed in degrees Celcius. At time $t = (n+1)\Delta t$, for the effect of :

- outdoor temperature : $\Delta t_{i1l} = \sum_{k=1}^{l_1} X_l(k)\,[t_o(n+2-k) - t_{il}(n+1)]_l$ (48)
- outdoor heat flux : $\Delta t_{i2l} = \sum_{k=1}^{l_2} Y_l(k)\,[\alpha I_G(n+2-k) - \varepsilon R(n+2-k)]_l$ (49)
- indoor radiative flux : $\Delta t_{i3l} = \sum_{k=1}^{l_3} Z_l(k)\left[\sum_w \frac{A_w \tau_w}{A_{total}} I_G(n+2-k) + \frac{Q_{rad}}{A_{total}}(n+2-k)\right]_l$ (50)
- indoor convective flux : $\Delta t_{i4l} = \sum_{k=1}^{l_4} W_l(k)\,[Q + Q_{conv} + \rho c_p \dot{V}(t_i(n+1) - t_o(n+1))] + \sum_{j=1,\, j\neq l}^{N} q_{lj}$ (51)

Those increments refer to the subvolume of the room's air associated to the wall "l". t_{il} represents the temperature of that subvolume. Usual notations are used for A, I_G, R, α , ε , etc, ... as defined previously. Q_{conv} and Q_{rad} stand for convective and radiative free gains loading the subzone and Q for its heating or cooling load.

X_l, Y_l, Z_l and W_l are the response factors and the quantities q_{lj} represent the eventual enthalpy exchanges that could occur between subvolumes of the room. Indices are the following :

- i refers to the room;
- n to the time considered;
- l to the wall considered;
- l_1, l_2, l_3, l_4 to the length of the 4 sets of response factos;
- w to the numbering of the windows.

Recalling now the assumption of a uniform temperature t_i throughout the room, we may state for all subzones :

$$t_{il} = t_i \quad \forall l \quad \text{at time } t = (n+1)\Delta t \tag{52}$$

In that case, all enthalpy fluxes will compensate each other.

Now, refering to the linearity of the problem, we may add all increments and define global increments for each subzone :

$$\Delta t_{il} = \sum_{p=1}^{4} \Delta t_{ipl} \tag{53}$$

The global increment of the room will be :

$$\Delta t_i = \sum_{l=1}^{N} \Delta t_{il} \tag{54}$$

where N stands for the number of walls limiting the room.

The increment Δt_i is defined with respect to the temperature t_i at time $(n+1)\Delta t$. If this temperature is a set point temperature, the heat balance equilibrium is obtained when :

$$\Delta t_i = 0. \tag{55}$$

The same condition applies if the temperature t_i is considered as free floating, as $t_i[(n+1)\Delta t]$ was used in the establishment of equations (48) through (51) and may thus be treated as an "instantaneous set point". Consequently, equation (55), where all contributions are introduced from (48) through (51), represents the heat balance of room i.

Expressing again similar calculations on all zones defining the dwelling, we shall obtain a system of linear algebraic equations of a similar form as equation (21) that can be solved at every hour for indoor temperatures, heat loads or any combination of both. Let us however note that the only time dependant terms of matrix $\underline{\underline{A}}$ are the diagonal terms, where the air infiltration rates appear. If those terms remain constant or take a limited number of values during the period covered by the computation, it is advantageous to compute the possible inverse matrices $\underline{\underline{A}}^{-1}$ previously to the hourly heat balances, in order to save computing time.

As the heat balance is expressed at every interval of time, it is possible to simulate all kinds of behaviours of the building's system : intermittent heating, loads in selected rooms only, limited power supplied, etc, ... They are all summarized by the simulation of regulation laws, as implemented in the program LPB-1 and available for each zone. Maximum heat supply and cooling possibility are to be prescribed as well as 4 characteristic room temperatures. Evidently, the powers may be set equal to zero or sent to infinity, while temperatures may be equal if necessary. The computer program will first compute the room's temperature without heat power. If it ranges between t_2 and t_3, the correct result is obtained. If the temperature falls out of this dead band, the program will include the corresponding load and iterate until convergence. It will then provide the resulting temperature and heating or cooling power. If the temperature ranges below t_1 or over t_4, it will stop computations and provide again temperature and load.

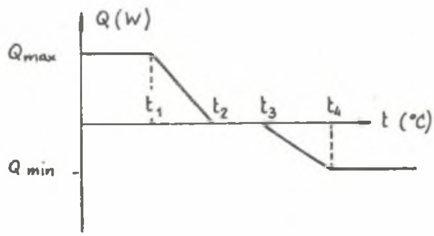


Fig. 11. Computation data
Rys. 11. Dane do obliczeń numerycznych

As an illustration of multizone dynamic computations, figure 12 presents the comparison of measured temperatures with simulation results. They apply to a large open plan office where a central core and 4 peripheral zones are defined. Their separation is simulated by purely resistive walls with global heat transfer coefficients of 50 W/m^2 °K in order to take into account convective exchanges between zones. Cooling loads provided by the air conditioning, occupancy and lightings were considered as free gains and actually measured meteorological data was used.

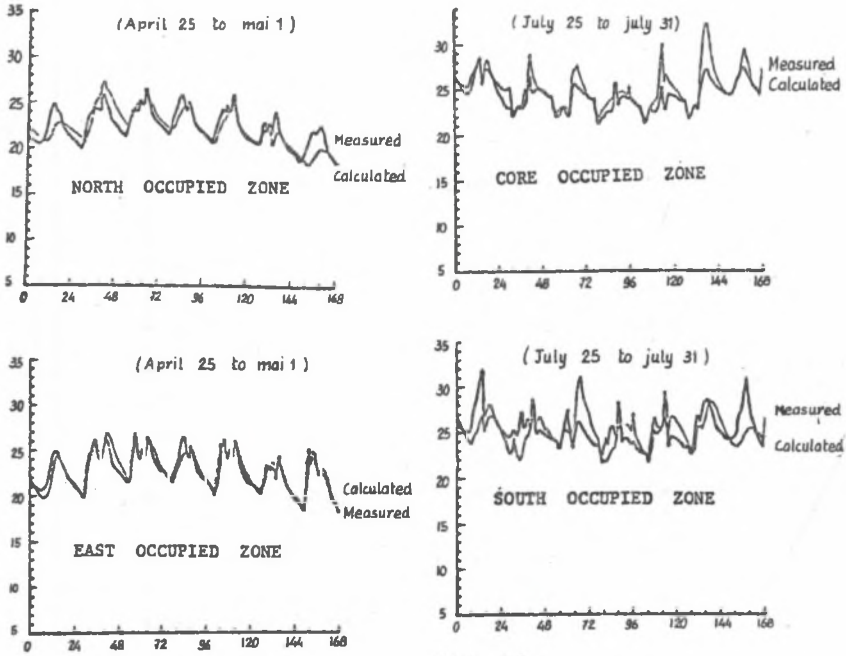


Fig. 12

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SYMULACJA KOMPUTEROWA DO OBLICZEŃ OBCIĄŻEŃ BUDYNKÓW
ORAZ KLIMATU WEWNĘTRZNEGO

S t r e s z c z e n i e

W pracy przedstawiono różne podejścia do obliczania temperatur wewnętrznych lub obciążeń cieplnych i chłodniczych zamieszkałych budynków mieszkalnych. Podano przegląd statycznych i dynamicznych wzorów wraz z ilustrującymi je przykładami. Przedstawiono również pewne uwagi dotyczące dostępnych danych dla obliczeń numerycznych obciążeń budynków oraz programów komputerowych opracowanych w Laboratorium Termodynamiki Uniwersytetu w Liege.

МОДЕЛИРОВАНИЕ С ПОМОЩЬЮ ВЫЧИСЛИТЕЛЬНОЙ МАШИНЫ ДЛЯ РАСЧЕТОВ НАГРУЗОК ЗДАНИЙ И ВНУТРЕННЕГО КЛИМАТА

Р е з ю м е

В настоящей работе указан разный подход к расчётам внутренних температур, а также тепловых и холодильных нагрузок заселённых жилых зданий. Кроме того, в работе даётся пересмотр статических и динамических формул вместе с примерами. Представлены тоже некоторые замечания, относящиеся к доступным данным для численных расчётов нагрузок зданий и числовых программ, разработанных в Лаборатории термодинамики Университета в Льеже.