UNDERSØKELSE AV TRE DATAMASKINPROGRAMMER FOR BEREGNING AV ROMKLIMA

(INVESTIGATION OF THREE COMPUTER PROGRAMS FOR CALCULATION OF INDOOR CLIMATE)

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Undersøkelse av tre datamaskinprogrammer for beregning av inneklima.

(Investigation of three computer programs for calculation of indoor climate)

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Tre datamaskinprogrammer for beregning av termisk inneklima er sammenlignet ved at de er gitt samme oppgave. Første fase av arbeidet viste nødvendigheten av å koordinere inn-data fordi mange paramtre avhenger av brukerens vurdering. Etter at dette var gjort, samtidig som innebygde betingelser i programmene ble klarlagt, viste resultatene god overensstemmelse. Rapporten kan brukes som en nordisk referanse for slike beregninger.

Emneord:

Romklima
Datamaskinprogrammer
Nordisk harmonisering

FORORD

I en NKB*-komitê som arbeider med normer for inneklimaet, ble det reist spørsmål om ulike beregningsmetoder for det termiske inneklima gir sammenlignbare resultater. Datamaskinprogrammer fra Norge, Sverige og Finland som beregner inneklima ble testet og dette er gjort rede for i denne rapporten.

Arbeidet i NKB har gått parallelt med prosjektet "Bygningen, klimaet og klimaanlegget", som har til hovedformål å finne innflytelsen fra viktige parametre på bygningers energiforbruk. Da rapporten bør ha stor interesse innenfor dette, er det valgt å gi den ut som en del av prosjektets publikasjonsserie. Rapporten er også trykket på KTH, Stockholm og den er presentert på "The Seventh CIB Congress" i Edinburgh, september 1977. Av den grunn har den fått engelsk språkdrakt.

Tidligere utgitte rapporter i prosjektet "Bygningen, klimaet og klimaanlegget" er:

1. Kontroll av enkel rommodell for varmebalanseberegninger, mai 1976.

2. GHMET - Program for utvelgelse av meteorologiske data, september 1976.

3. Betydningen av krav til rettet operativ temperatur, oktober 1976.

4. Undersøkelse av avtrekksvindu, desember 1976.

5. Energiforbruk i klimasystem med avtrekksvindu og varmeveksler, mars 1977.

6. Energiforbruk i en-kanals klimasystem, november 1977.

Trondheim, desember 1977

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*NKB = Nordisk Komitê för Bygnadsbestemmelser

Summary

A comparison of three computer programs designed to calculate room air temperature and loads has been made as part of an international effort to establish common regulations for the internal environment.

The main purpose was to harmonize the programs for internal use. However, regulations are also needed for calculation methods on which the programs are based. The three programs are all based on different calculation methods.

BRIS - a Swedish program using a finite difference method

BYVOK - a Norwegian program using the thermal response factor method

HEAT - a Finnish program using a polynomial solution and the thermal response factor method

An ordinary office in a multistorey building was chosen as a room model. First of all the temperature in the room without a window was calculated, then with internal loads at daytime, and lastly with a window included.

The first phase of the work showed the necessity of coordinating the input data, because normally the determination of many important parameters are up to the user. Also assumptions are built into the programs themselves. A number of details such as the window heat balance equations, algorithms for calculation of solar irradiation, convective heat transfer coefficients etc. were therefore compared and found to be of importance.

Careful coordination of input data produced results with only minor discrepancies.

It would appear that the attempt to harmonize these programs was successful and the results can be used as a reference for other calculation methods. However further case studies will be necessary to provide a basis for regulations.

CONTENTS

1. INTRODUCTION

The Nordic Committee for Building Regulations (NKB) is currently engaged in drafting a set of standards on thermal indoor climate. NKB would like to make it feasible to check out calculations in connection with project planning. If this is going to be meaningful the methods of calculation used must produce en equivalent result.

Whenever indoor temperatures or cooling requirements under summer conditions have to be estimated, it has proved necessary to resort to calculation models of the kind that best lend themselves to computerization.

A number of such computer programs exists today. International comparisons have been made earlier. Figure 1 shows that the results disperse very widely. Probably one of the reasons is that input data have not been sufficiently well-defined, but it is also likely that different calculation models contain various simplifications which have more or less serious consequences for the result (the cooling requirements arrived at are usually too high).

Three relatively sophisticated programs have been compared in this paper:

- I The BRIS program, developed with support from the Swedish Council for Building Research by the Department of Heating and Ventilating Engineering at the Institute of Technology in Stockholm.
- II The BYVOK program, developed by the Department of Heating, Ventilating and Sanitary Engineering at the Norwegian Institute of Technology in Trondheim.
- III The HEAT program, developed by EKONO OY in Helsinki.

The goals set for this project are:

- o to harmonize the above-named programs so that they can be used in the preparation of indoor climate standards;

- o to create a basis for comparisons of other programs and calculation methods with future standardization in mind.

This requires a considerable effort, and a detailed set of goals for it could be:

- o to standardize necessary input data, what form they should have and how they can be determined with the aid of material available in the planning base;
- o to specify accurate calculation results with permissible margins of error for indoor climate, cooling and heating requirements. For this purpose some typological structure is to be designed to see how it works under different climatic conditions;
- o to analyze sensitivities to important parameters which have great bearing on the calculation result;
- o to verify the calculation result with measurements.

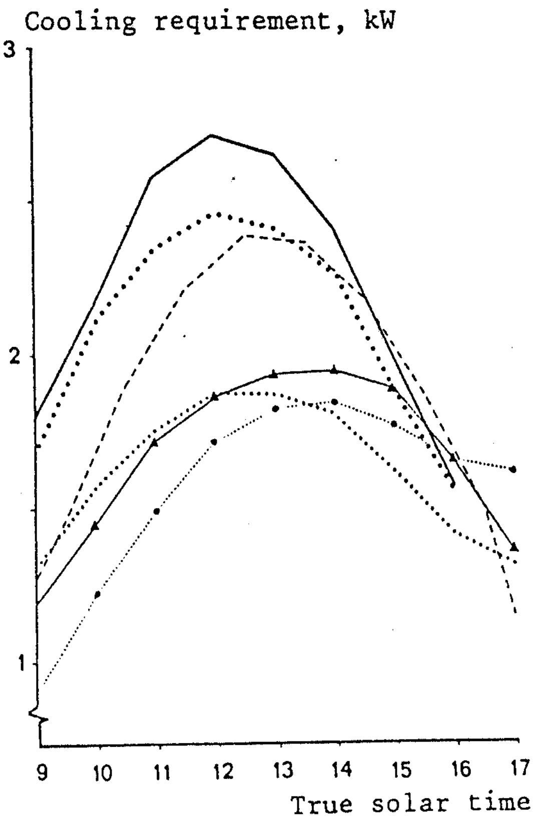


Fig. 1 Cooling requirement for one and the same case calculated with different computer programs according to a comparison that has been made within REHVA.

2.1 Description of BRIS

This program was developed by Gösta BRown, Axel BRing and Engelbrekt ISfält, and funded for the most part with grants awarded by the Swedish Council for Building Research. Since the program was mainly intended for research purposes from the very outset, unnecessary approximations have been avoided.

The Fourier heat equations are solved numerically (using the Crank-Nicolson method). The long-wave radiant exchange indoors is calculated using Stephan-Boltzmann's law. The short-wave radiation transmitted through windows is distributed with reference to reflectivity of the room surfaces (by means of distribution coefficients).

The convective heat transfer coefficients are calculated on the basis of prevailing temperature conditions, but may also be chosen freely. Considering that the temperature-dependent boundary conditions make the system nonlinear, the solution is worked out using the relaxation method.

A consistently pursued quest in the development of BRIS has been to make the program flexible so that shifting objects of calculation can be handled. Hence the data array is not fixed, this to permit the various types of blank forms which occur to be combined in many different ways. The forms are tied together with cross-references.

Calculation period and calculation step may be chosen arbitrarily. The usual calculation period is a 24-hour day and the calculation step is 0.5 hours. Whenever periodically stationary states are desired, use can be made of a forecast which is based on an exponential extrapolation. The forecast can be suppressed to permit studying the whole building-up process.

Walls and beams can be freely defined. Data are built into the program for ten or so ordinary building materials, which are specified only by code (a letter) and thickness. Thermal data must be specified for other materials. Thermal resistance can be indicated for layers between materials. The outer boundaries of walls and beams can be set in various ways:

Identical rooms
Other room dealt with at the same time
Symmetry surface where the temperature gradient = 0
Façade with given temperature and radiation conditions

This makes it feasible to handle a broad spectrum of calculation objects ranging from cubicled offices to stand-alone buildings.

Windows may be optionally placed within the room´s boundary surfaces.

A heating unit is defined to mean that radiation on the back is exchanged for a wall lying behind, and radiation on the front for other room surfaces having regard to the angular coefficients. The convection coefficient of heat transfer depends on temperature in the same way as at vertical surfaces. The convection part is multiplied by an area magnification factor whose size will depend on the design of the heater. The heater has its own thermal capacity.

Surface heat sources of given output and radiation propotion may be placed along the room surfaces or parts of these. Illumination sources can be thus described to advantage.

Time-dependent data are all described in similar fashion. Variations during the calculation period are described with discrete values in intervals which may vary arbitrarily during the period.

Classified as time-dependent data are: temperature of the outdoor air, flow of leaking air, temperature of the room air, temperature and flow of the supply air, convective effects, insolation on façades, film coefficients of heat transfer at façade surfaces, insolation through windows, shading coefficients and $\underline{k}$ values of windows, lighting effects and output of the heating unit. The magnitudes which enter into the room air´s heat balance equation, and which in the reality can be controlled by means of installations, may be sought either one by one -- with given values necessarily imputed to other variables -- or in pairs, with given values to be construed as limits (max. or min.). The calculation is controlled by a code which states which magnitude or magnitudes are to be sought. The code is classified with time-dependent data and as such may be varied during the calculation period. In consequence a number of systems and operating cycles may be simulated.

Climatic data may be generated by the program if so desired. Insolation is calculated on the basis of information about date, the town's geographic locus and compass points. The outdoor temperature is obtained from diurnal mean, amplitude and clock stroke for maximum value.

Operative temperatures (directional or weighted for six directions) can be calculated for arbitrarily chosen points in the room.

For selected time segments during the calculation period (e.g. hours of work) a mean value calculation is made as well as a tabulation showing the percentage distribution of the operative temperatures.

The BRIS program is mostly written in ALGOL, with certain sections and special arragements in assembler code. Its original version is to be found with computer TRASK 2 on the premises of the software company, Datasystem AB, in Stocksund northeast of Stockholm. A version translated into FORTRAN is used by DALAB Installationsberäkningar AB in Solna northwest of Stockholm.

Although the program varies in size depending on the object to be calculated, i.e. on the number of variables and machine type, it can be estimated to be at least 80 to 100 kilobytes.

The costs of performing one run is very much a matter of the object to be calculated. Several rooms and thick walls increase the number of variables in the system. Heavy structures have long building-up times. For a single room with symmetric surroundings the costs of machine time for a complete run up to periodic-stationary state may range anywhere from 50 to 100 Swedish kronor.

2.2 Description of BYVOK

BYVOK (from the Norwegian "Bygningen varme- och kjølebehov", meaning "heating and cooling requirements of buildings") is the name of a programming system built up to model the complex consisting of outdoor climate, building and indoor climate. This program provides the periodic-stationary solution to the equation system.

The outdoor climate is represented by outdoor temperature and solar radiation. Temperature may be stated hour by hour, or through maximum and minimum values and corresponding points in time. Solar radiation is calculated with equations stated in ASHRAE etc. Hourly values are obtained during the day from direct and diffuse (including ground-reflected) radiation and the sun's position. For a given façade direction the angle of incidence of the direct solar radiation is also obtained.

Special weight has been attached to the building for purposes of meticulous simulation. Its starting point is a room placed midway in a façade surrounded by identical rooms and as such has only one outer wall.

The window may consist of an arbitrary number of layers. Optical and thermal data are taken as inputs to calculate that transport of heat through the window which is caused by the sun. Solar radiation is assumed to be diffuse after passing through the window and is distributed among the room surfaces as a function of reflection factors and angular coefficients.

Every room surface is counted isotherm, which means that it will exchange long-wave radiation with other room surfaces. To simplify the calculation it is assumed that the surfaces do not reflect long-wave radiation and that the mean temperatures are given. This makes it possible to obtain a linear correlation with a heat transfer coefficient. The angular coefficients are determined on the basis of the room's geometry.

The calculation of heat flows in walls, roofs and floors complies with the response factor principle. Walls and beams may vary in composition and consist of several layers. The response factors are calculated for intervals of 1/8 hour, but are converted into hourly values. As soon as periodic stationary states have been reached, combinations of disturbances and response factors going infinitely far back in time can be obtained as the sum total of a geometric series. The room´s heat balance is also described in conformity with the response factor principle so that this is used through the whole program.

The thermal load imposed by people and machines is counted in strictly convective terms, whereas the lighting effect is divided up into radiation and convection all according to the workmanship (freely suspended lighting fixtures, ceilings, etc.). Ventilated lighting fixtures can also be taken into account.

To begin with the response factors are calculated for the room model´s unknown temperatures with regard to different excitations. With values given for the convection coefficients of heat transfer, a conversion is made into response factors for heat flows. These are used to calculate heating and cooling requirements.

The indoor climate is described in the present program version only by means of the room air temperature. One reckons with an ideal mixture of the air, i.e. that the temperature is the same in the whole room.

To begin with the room air temperature is given a constant value for the 24-hour day. This value is used to postulate the calculation of other temperatures and heat flows.

Additional provision is made to calculate the change in the total flow of heat to the room air having regard to the latter´s temperature. This new response factor makes it feasible, starting out from the heat flows at constant room air temperature, to calculate other operating conditions. Examples of such are ventilation with outdoor air, constraints on cooling capacity and intermittent operation. Efforts to insert directional operative temperature into the program are now in progress.

A characteristic feature of the response factor method is that once the responce factors for a particular room are calculated, complete enumerations of different conditions can be speedily performed. On the other hand, as contrasted with the use of different methods, no information will be provided about discrete temperatures and heat flows unless special calculations are made.

A decided drawback of this method is the insistence on linearity. By and large, however, this criterion is satisfied for the temperature differentials that prevail in the room. Probably the biggest error appears because the convection coefficients of heat transfer are constant.

The program is written in ALGOL and FORTRAN and takes up about 40 k-words of 36 bits each in a UNIVAC 1108. Generation of a set of excitations (solar data, outdoor temperatures, inner heat sources), calculations of response factors and combination of these take about 40 seconds of Cpu-time at a market price of about 120 Norwegian kronor. As soon as the response factors are determined, complete enumerations can be rapidly carried out for different cases.

2.3 Description of HEAT

To calculate indoor climate, heating or cooling effects under non-stationary conditions, a model has been developed in Finland which separately deals with concurrently appearing heat transfer mechanisms (short-wave radiation from sun and illumination, long-wave radiation and convection). The heat balance in outer walls and roofs is worked out using the response factor method, which can be adapted to an arbitrary wall design. This method uses a separate program to enumerate the characteristic series for each wall type. With these series the program describes the action of temperature pulses aimed at the surface on the heat flow in the inner surface.

The solution for symmetrical partitions and beams, whose temperature and heat flow are identical on both sides of the wall, is based on approximating the wall's temperature distribution with a fourth-degree polynomial for each time period. An unsymmetrical wall is understood to mean a wall on the one side of which the temperature is constant, while on the other side the temperature varies as a function of time. In computational terms this is a special case of a symmetrical wall. The model contains exact balances for windows, variously integrated ceiling solutions and other special structural designs.

The following aspects were given special weight when the computer program was prepared:

1. It should be feasible to simplify the filling-in of input data by making use of prefabricated structural members.
2. Individual balances for all occurring types of room surfaces should be accomodated in the program.
3. It should be feasible to perform calculations for intervals of varying length, for instance to permit the study of building-up processes.

The filling-in of input data is largely confined to choice of type. For several cities or towns the weather data of the dimensioning 24-hour day, relating both to winter and summer conditions, have been stored in disc memory units. Central ~~processing units~~ and ~~follow-up devices~~ (perhaps placed in the room) can be selected by code number from the group for the most common installation solutions.

A number of wall types can be thermally identified only by means of code numbers. The medium of input data conveys information about dimensions of the walls, colours of the room surfaces and insulating cover, if any, e.g. sound absorbers or carpets. These are treated as thermal resistance without mass.

The codification is not binding; on the contrary, all particulars can be put into the very form that the user wants in case the desired portion is not to be found among the pre-codified types.

The loads to which the room is subjected, in the form of lighting, persons and installations, can be divided into morning and afternoon intervals.

A number of different window types can be defined in the program by combining layers of ordinary, absorbing or reflecting glass, Venetian blinds, etc. The window balance goes in its entirety into the room air balance. In establishing the window´s heat balance, the mass of the glass was left out of account because it is insignificant.

The ceiling members differ from one another primarily by virtue of the degree of integration. As for the window, an internal heat balance is specifically determined for the ceiling. In the balance the mass of the lowered roof is assumed to be nonexistent. The roof tile´s balance is counted as for a corresponding wall panel.

In addition to the actual walls the program contains the heat balance for a radiator. Elevated temperature of the wall behind is to be borne in mind.

To clarify the influence exerted by the limited duration of extreme weather conditions, the calculations are normally performed for a two-day period. The starting situation chosen is the stationary state that would supervene with diurnal means for outdoor climate and inner heat sources.

The heat balance calculations are performed with a half-hour time step. If necessary a four-day period may also be completely figured out, in which case the calculation step is one hour.

The HEAT program is inserted in EKONO´s DEC 10 system and is written in FORTRAN. Requisite memory space is about 23 k-words of 36 bits each. Normally, the calculation period takes about 130 seconds of Cpu-time. The Cpu cost at normal billing price without program rental then works out at about 97.50 Finnish marks. Additional costs will arise when input data are fed in, for time-sharing and, in exceptional cases, for generation of response factors and weather data.

Work on certain additional facilities and changes is progressing, the stated aims being as follows:

- o Longer periods (8 days to 1 year) are to be made amenable to complete enumeration (the present limit is 4 days).
- o It should be feasible to cut down on computer time. The number of iterations falls off sharply if the convection coefficients of heat transfer are held constant.
- o Operative temperature and directional operative temperature are to be introduced (partly carried out).

3. CALCULATIONS

3.1 Introductory runs

To begin with a calculation was made with the BRIS program relating to a cubicled office under summer conditions. The same case was counted through with HEAT and BYVOK. Poor congruence was found and it turned out that the preconditions were marred by many obscurities.

- o The insolation values generated in each program were not really alike.
- o The distribution in the room of the transmitted solar radiation was differently handled (BRIS and BYVOK use distribution coefficients).
- o Different values were assigned to temperature elevation of the supply air owing to the operation of fan installations (0 or $1^{o}C$).
- o Heat transfer coefficients for convection and long-wave radiation were unlike.
- o The boundary conditions on the corridor wall outside were unlike.
- o The HEAT program counted as above on a starting approximation + 2 days, BRIS and BYVOK on a built-up process.

To make a comparison meaningful it was obviously necessary to try to eliminate all these disparities in the preconditions and to analyze their importance.

3.2 New preconditions

Since BYVOK only counts periodic-stationary states and HEAT counts 2 (4) days, the results of these programs are not directly comparable. With BRIS both cases can be counted, making it feasible to compare BRIS with BYVOK and with HEAT.

Strategy for comparisons:

To start out with a very plain room is investigated without outer walls or windows, on which the only external action is a convective effect over a fixed time period. The results should make it feasible to analyze any differences between the various integration methods. Step by step an outer wall and a window are then introduced until we get to the case that was run by way of introduction.

General data

Room dimensions

- $3.5 \times 5.0 \times 2.7$ m^3
- Angular coefficients were calculated using the BRIS program.

Surface		
1	17.50 m^2	Roof
2	3.45 "	Outer wall
3	13.50 "	Partition
4	17.50 "	Floor
5	9.45 "	Corridor wall
6	13.50 "	Partition
7	6.00 "	Window

Angular coefficients

	1	2	3	4	5	6	7
1	0	51	200	326	137	200	86
2	257	0	207	257	91	188	0
3	259	53	0	259	139	204	86
4	326	51	200	0	137	200	86
5	254	33	198	254	0	198	63
6	259	48	204	259	139	0	91
7	252	0	192	252	100	204	0

Structures

Walls

l = 0,03 m

λ = 0,12 W/m K

ρ = 400 kg/m^3

c_p = 1000 J/kgK

Roofs and floors

l = 0,20 m

λ = 1,75 W/m K

ρ = 2300 kg/m^3

c_p = 840 J/kgK

Run 1

Symmetric wall

The room temperature and/or the heat flow against the walls is figured out for the case:

- o room in inner zone, no window
- o all surfaces symmetric (thermal)
- o convective load inside, 500 W, 0800-1600 hours
- o no ventilation
- o heat transfer coefficients as per each program´s own values
- o opening temperature +20°C in the whole structure

Run 2

Importance of the convection coefficients of heat transfer.

Same input data as in run 1, but heat transfer coefficients from the BYVOK program were used.

This run deleted when erroneous values were fed into BRIS.

Run 3

Unsymmetric wall

Same input data as in run 1, but all 4 walls unsymmetric.
All walls have a constant temperature of +20°C outside.

Run 4

Outer wall

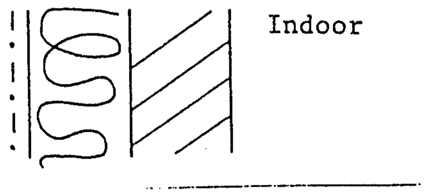
Room data same as in run 1, but this time there is a real outer wall.

- no inner heat sources
- no windows
- outer wall faces south
- ventilation with outdoor air 0.0016 kg/s, m^2 = 101 kg/h all day long

Outdoor

α_y = 16 W/m^2,K

a_{sol} = 70 %



Indoor

Insulation	Concrete	
l = 0,10	0,10	m
λ = 0,04	1,75	W/mK
ρ = 100	2300	kg/m^3
c_p = 840	840	J/kgK

Climatic data

Outdoor temperature 20 $\pm$ 5.5 sinus-shaped with max. at 1500 hours

Solar radiation is calculated for:

o	latitude	60.00	ground reflection 0.0
o	longtitude	15.00	
o	date	15.07	

Climatic data are given in the table below:

Hour	Outdoor air	Radiation on horizontal surface			
	°C	Direct W/m²	Diffuse W/m²	The sun´s elevation angle	azimuth angle
0	16,1				
1	15,2				
2	14,7				
3	14,5				
4	14,7		24	4,6	54,2
5	15,2	95	58	10,9	66,7
6	16,1	188	94	18,0	89,9
7	17,2	278	124	25,5	92,4
8	18,6	374	146	33,0	105,4
9	20,0	445	180	39,7	120,9
10	21,4	520	204	45,4	138,3
11	22,7	550	228	49,7	158,1
12	23,9	570	246	51,0	180,0
13	24,8	550	246	49,7	201,9
14	25,3	520	238	45,4	221,7
15	25,5	445	226	39,7	239,1
16	25,3	374	200	33,0	254,6
17	24,8	278	140	25,5	267,6
18	23,9	188	102	18,0	280,9
19	22,7	95	64	10,9	293,3
20	21,4	-	30	4,6	305,8
21	20,0				
22	18,6				
23	17,2				
24	16,1				
Mean	20,0				

Run 5

Clear two-pane window

Same input data as in run 4, but now the outer wall has a window.

Window dimensions (glass surface)
- width 3.0 m
- height 2.0 m

Both panes of the window are clear. The glass has the following optical properties:

a) direct radiation

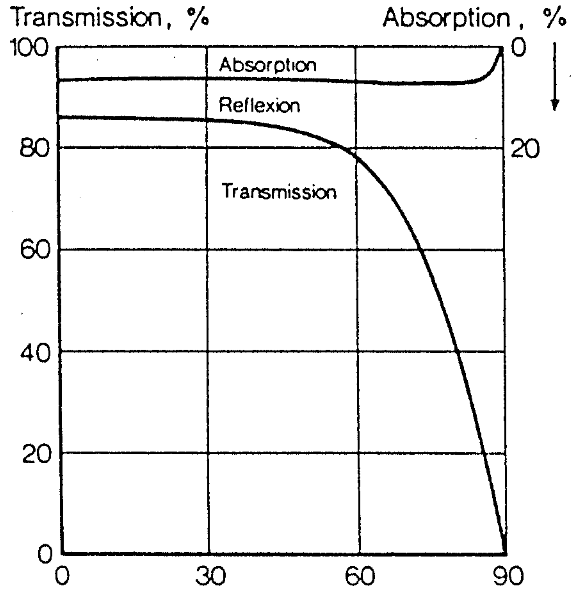


Fig. 3.2.1 Transmission, reflection and absorption for a pane of ordinary window glass.

Or, in table form:

i^o	0	10	20	30	40	50	60	70	80	90
T	0,86	0,86	0,86	0,86	0,85	0,82	0,77	0,68	0,43	0,00
R	0,08	0,08	0,08	0,08	0,09	0,12	0,16	0,25	0,50	1,00
A	0,06	0,06	0,06	0,06	0,06	0,06	0,07	0,07	0,07	0,00

b) diffuse radiation

The diffuse (and reflected) radiation has an incidence angle of 0^{o}.

Short-wave radiation has a reflection coefficient of 0.25 for the window´s inner surface, of 0.5 for other room surfaces.

3.3 Comparison of BRIS with HEAT

Run 1

Figure 2 portrays the curve that room-air temperature takes when a convective heat source loads a room that is bounded by inner walls only. There is no ventilation. The temperature´s rise rate turns out to be greater in the BRIS program (0.28 K/h) than in the HEAT program (0.24 K/h). A difference is distinctly noticeable at the peak temperatures (BRIS 28.14°C, HEAT 26.9°C). On the other hand temperature increase per day for the masses in both programs (BRIS 2.03 K, HEAT 2.0 K) is the same as that figured out of the energy flows by hand, 2.03 K.

Inasmuch as the energy quantum that is diurnally stored in the structure of both programs agrees with the energy quantum that is fed into the room, one may assume that the solutions for the room balance are correct.

Reacting on the temperature´s rise rate and attained peak value is the heat transfer between the room air and the walls, and to some extent also the radiation heat flows between the room surfaces. A high heat transfer coefficient signifies a heavy damping down of the air´s temperature changes -- a low heat transfer coefficient signifies the opposite.

BRIS approximates temperature gradients within each wall layer with straight lines, while HEAT assigns a fourth-degree polynomial. If the division into layers is a rough one, this may give rise to differences of heat transfer at the surfaces.

To find out about the action attributable to the convection coefficient of heat transfer, a supplementary run was made with application to HEAT of heat transfer coefficients used in the BRIS program. The radiation exchange was calculated in normal fashion in each program, i.e. in HEAT with a constant heat transfer coefficient for radiation equal to 5.2 W/m^2 K and in BRIS with the aid of Stephan-Boltzmann´s law.

The results in the latter case showed good congruence -- the temperature differential at most was 0.3°C, see Fig.2. Room air will not describe exactly the same temperature curve in the programs despite a standarization of the heat transfer coefficients. That is because of the aforementioned differences in the method of calculating radiation exchange and thermal conduction in walls and beams.

Run 3

With respect to unsymmetric inner walls, Fig.3, the same tendency is noticeable as in run 1: in HEAT the room is perceptibly heavier than in BRIS. The temperature differential during the loading period is about 0.8°C and outside the loading period about 0.2°C. Temperatures are nearly identical in their rise rate and cooling rate.

No difference of thermal conductance in an unsymmetric wall can be observed in this run. The variances of room temperatures may be considered, as in run 1, to be chiefly attributable to the heat transfer coefficients.

Run 4

In this case the room is loaded with heat that is transmitted through the sunlit outer wall. Owing to the ventilation the temperature variances will be small. The mean temperature looks like being the same, but the amplitude in BRIS is 0.4°C greater than in HEAT, see Fig.4.

Run 4 b

Figure 5 shows the variation of room air temperature with a convective load of 500 W at 0800-1600 hours. The difference is about 0.6°C. The tendency resembles that found for the earlier runs: the

HEAT program has a greater damping-down effect than BRIS.

Run 5

Figure 6 shows the variation of room air temperature after an unprotected two-pane window was inserted in the outer wall. The biggest difference that can be observed is about 1.8°C. The maximum temperatures diverge by about 1.3°C and the time displacement is about 1 hour. In contrast the diurnal mean temperatures are roughly alike.

With the HEAT program a run was made using those values for the convection coefficients of heat transfer that are used in BRIS. The difference between the maximum temperatures fell off from 1.3 to 1.0°C, an insignificant change.

A minor variance (about 2 %) in the short-wave radiation transmitted through the window can be recorded: BRIS uses 412 and HEAT 404 W/m^2 at 1200 hours. The difference is due to using slightly different methods to calculate the transmission of the diffuse radiation.

The distribution of the short-wave radiation acting on the room's various surfaces showed sizable differences:

Surface	BRIS	HEAT
floor	34.9 %	65.6 %
roof	13.4 %	9.9 %
outer wall	3.3 %	1.9 %
partition	14.0 %	7.2 %
corridor wall	9.4 %	5.0 %
window	10.9 %	3.3 %

The explanation of a greater damping effect for HEAT compared with BRIS may be assumed to lie in this difference. In HEAT the greater part of the short-wave radiation is absorbed by the massive flooring tile. The floor has a thermal capacity noticeably greater than that of the light partitions, thereby increasing its temperature and at the same time emitting heat slowly to the room air.

Evaluation of the results

Although the results from the HEAT and BRIS programs contain clear differences, the solutions are very much alike one another in principle. The differences seem to be chiefly due to the basic assumptions about heat transfer coefficients, about how the short-wave radiation hits the room´s surfaces, about starting approximation, etc.

The convection coefficient of heat transfer and its temperature dependence matter when the room temperatures are calculated. When insolation through windows and ventilating heat form the dominant items in the thermal balance, the significance is small. For purposes of determining output requirements the effect may be greater, but this aspect has not been investigated more closely in the present study.

With regard to the window´s heat balance there are certain dissimilarities whose effects are deserving of further study. The same holds for the significance of dissimilarities in the distribution of the short-wave radiation.

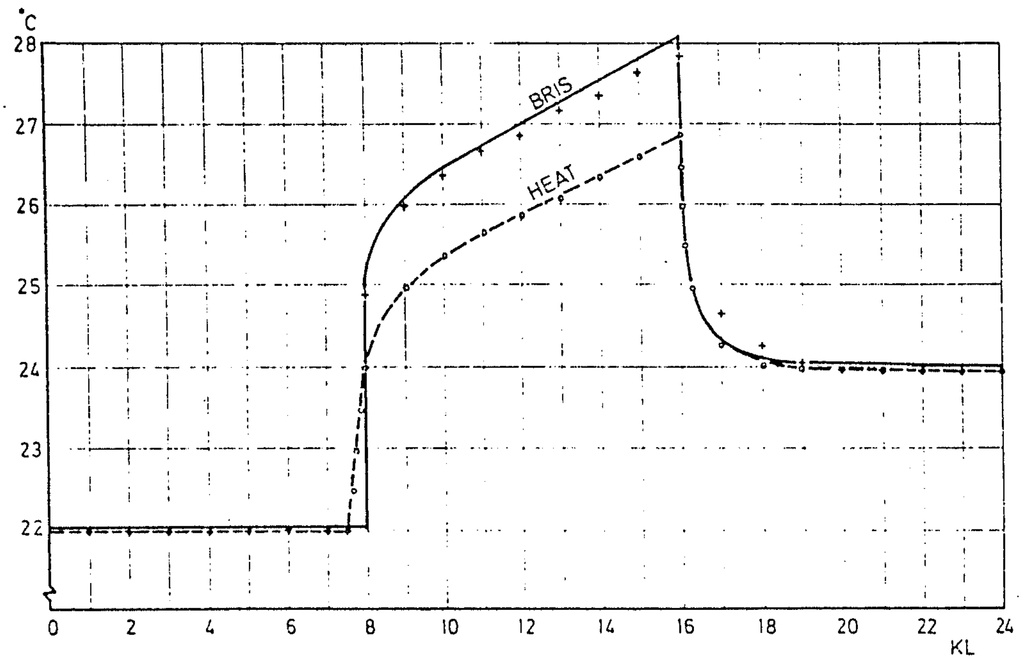


Fig. 2 Run 1. Room in inner zone, symmetric surroundings. Day 2; Starting temperature +20°C. ++ HEAT with the BRIS program´s values for the convection coefficients of heat transfer.

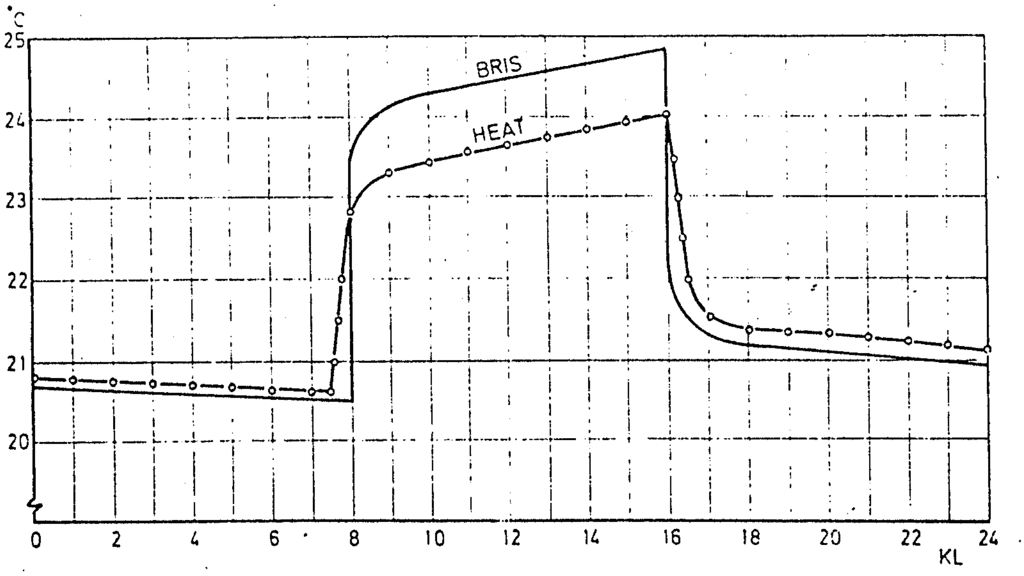


Fig. 3 *Run 3. Room in inner zone. Unsymmetric walls. The walls' outer surfaces are coupled to the ambient temperature of 20°C via a constant heat transfer coefficient = 9 W/m², K. Beams symmetrical. Day 2; Starting temperature 20°C.*

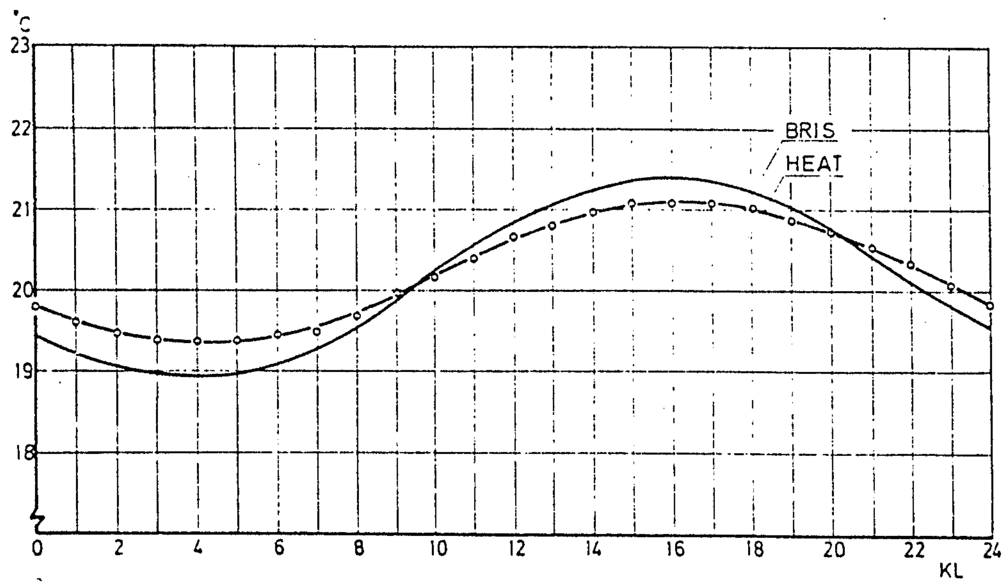


Fig. 4 *Run 4. Room with sunlit outer wall. No internal load. Day 2.*

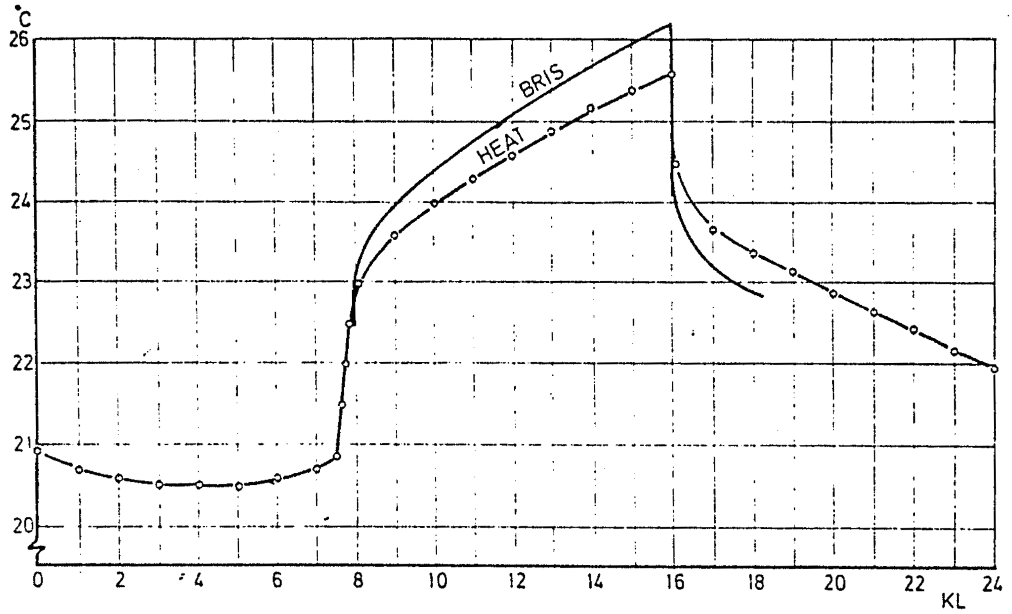


Fig. 5 Run 4 b. Room with sunlit outer wall. Convective load 500 W, 0800–1600 hours. Day 2.

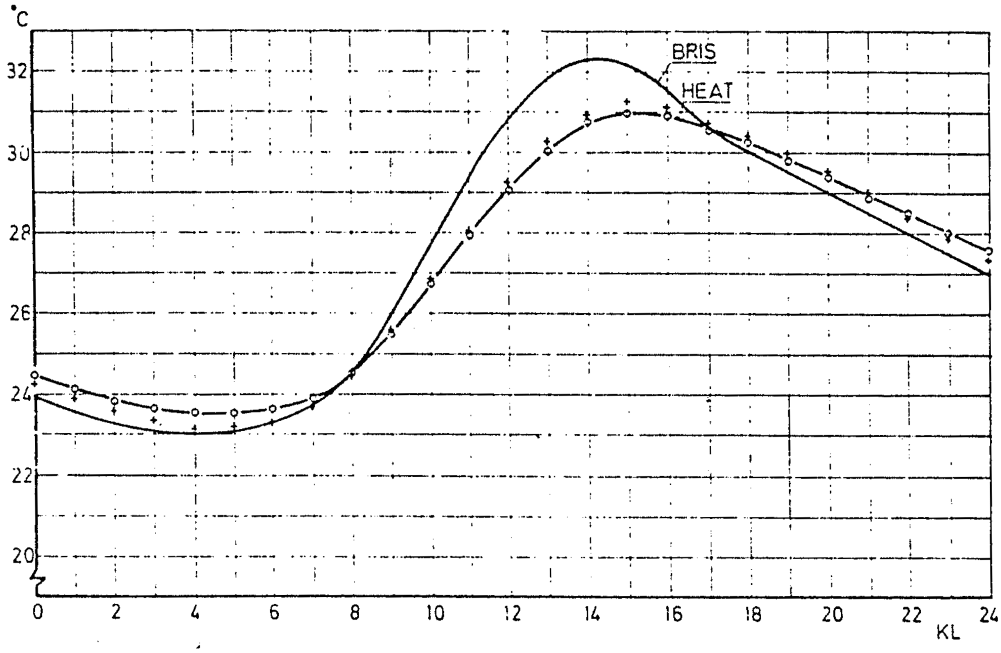


Fig. 6 Run 5. Room with outer wall and window. ++ HEAT using the BRIS program's values for the convection coefficients of heat transfer. Day 2.

3.4 BRIS compared with BYVOK

Run 4 a

Figure 7 shows the variation in room air temperature when the room is not loaded internally. The diurnal mean values seem to be alike, but BRIS gives an amplitude which is about 0.5°C greater than BYVOK.

Various heat flows enter into the heat balance which determines the temperature at any one moment: the heat stored in the inner walls, the heat flowing through the outer wall and the heat transported through the ventilating air. The latter is simply determined and calculated in the same way in both programs.

Since the diurnal means are the same, the estimated flow of heat through the outer wall has been the same, too. It is therefore likely that the difference of results stems from the different methods used to determine the heat storage. This problem is more closely investigated in run 4 c.

Run 4 b

Here the room is loaded with a convective effect, equal to 500 W at 0800-1600 hours, which of course produces a higher temperature level than in run 4 a (Fig. 8). Otherwise the tendency is the same: the diurnal means are alike, but BRIS gives a greater amplitude than BYVOK. Here the absolute temperature differential is somewhat greater, about 1°C.

Run 4 c

Here the room air temperature is held constant at 20°C and calculation is made of the convective effect required to compensate for the heat transmitted through the outer wall. Even though the air temperature is constant the temperature in inner walls and beams will vary because heat is transmitted from the inside of the outer wall by long-wave radiation. The effect which must be removed will therefore be damped down and delayed compared with the effect which the outer wall transmits. The diurnal mean value will naturally be the same.

Figure 9 shows that BYVOK damps down the cooling requirement slightly more than BRIS does and that the curves are somewhat displaced over time. However, the diurnal energy differs negligibly, 625 Wh in BRIS and 653 in BYVOK (about 4 %).

Run 5

In this case a window is added to the room model and insolation becomes the dominant heat source. This raises the diurnal mean of the room air to about 35°C. The runs from BRIS and BYVOK show very good congruence both of means and amplitudes (Fig. 10).

Effect of the convection coefficient of heat transfer

As mentioned earlier a large part of the differences which appear may be due to the use of different values for the convection coefficients of heat transfer (Appendix A 1). These determine the thermal transmission between room air and room surfaces and therefore affect the heat flow through outer walls as well as the exchange of heat with the heat magazine, i.e. both diurnal mean and amplitude are affected. A lower convective heat transfer coefficient increases the amplitude of the room air temperature because the heat magazine is less utilized.

This is confirmed by supplementary runs with BYVOK where the convective heat transfer coefficient was set at 2.5 W/m^2, °C for all room surfaces. In runs 4 a, 4 b and 5, 4 W/m^2 °C was used for vertical surfaces and 5 W/m^2 °C for horizontals. The results of these extra runs are plotted on corresponding diagrams for the original runs (Figs. 7 and 8).

In runs 4 a and b the amplitude differential vis-a vis BRIS is substantially reduced. The mean value does not change noticeably, but this is natural in a windowless room where the outer wall´s principal heat resistance lies in the insulation. (A change in the convective heat transfer coefficient causes a marginal change in the total heat resistance).

In run 5 the short-wave insolation through the window constitutes the dominant effect. It is directly absorbed by the room surfaces and effectively damped down in consequence. It is therefore reasonable to imagine that the convective heat transfer coefficients here have less of an impact. Run 5 with the value 2.5 W/m^2 ^{o}C changes the amplitude no more than negligibly, but does lower the diurnal mean a bit. The latter is explained by the fact that lower convective heat transfer coefficients result in less heat being transmitted from the solar-heated room surfaces to the room air. On the other hand the outer wall´s k-value will be lower, the result of which is to reduce the average heat losses during the 24-hour day. However, this action is insignificant, even for the window.

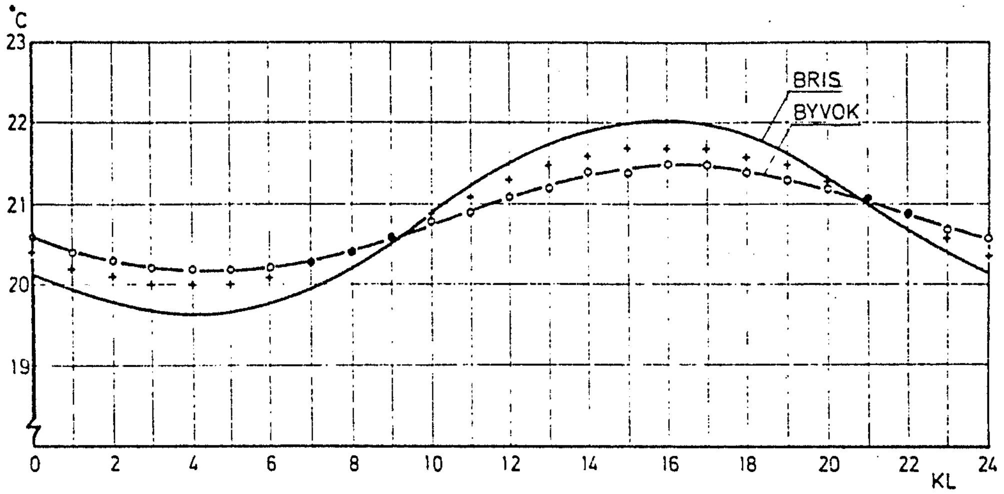


Fig. 7 Run 4 a. Room with sunlit outer wall. No internal load. Built-up. ++ BYVOK with α_k = 2.5 W/m^2, K.

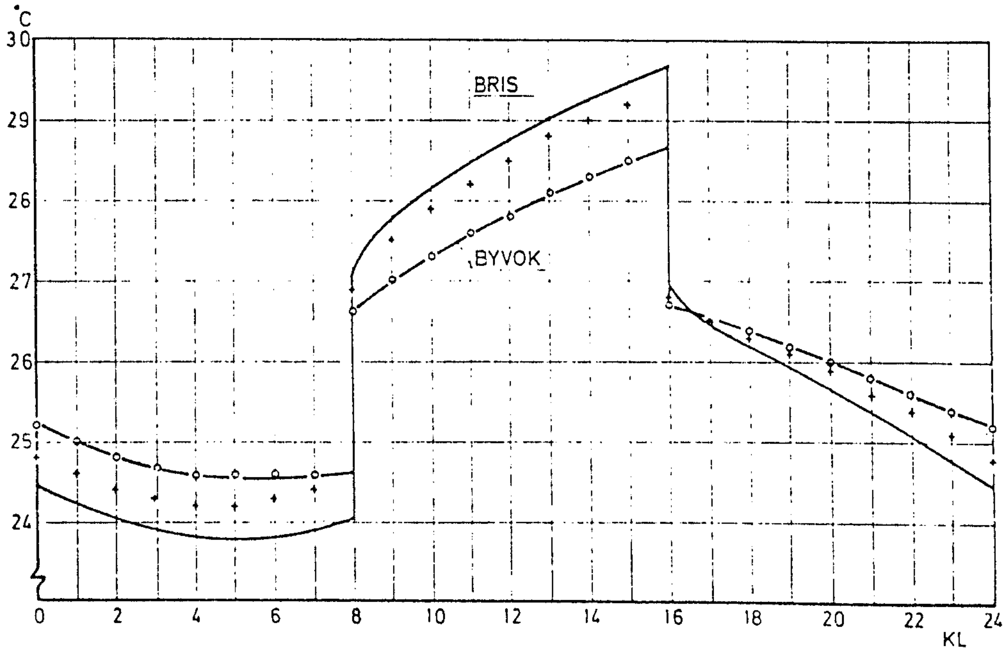


Fig. 8 Run 4 b. Room with sunlit outer wall. Convective load 500 W, 0800-1600 hours. Built-up. ++ BYVOK with α_k = 2.5 W/m^2, K.

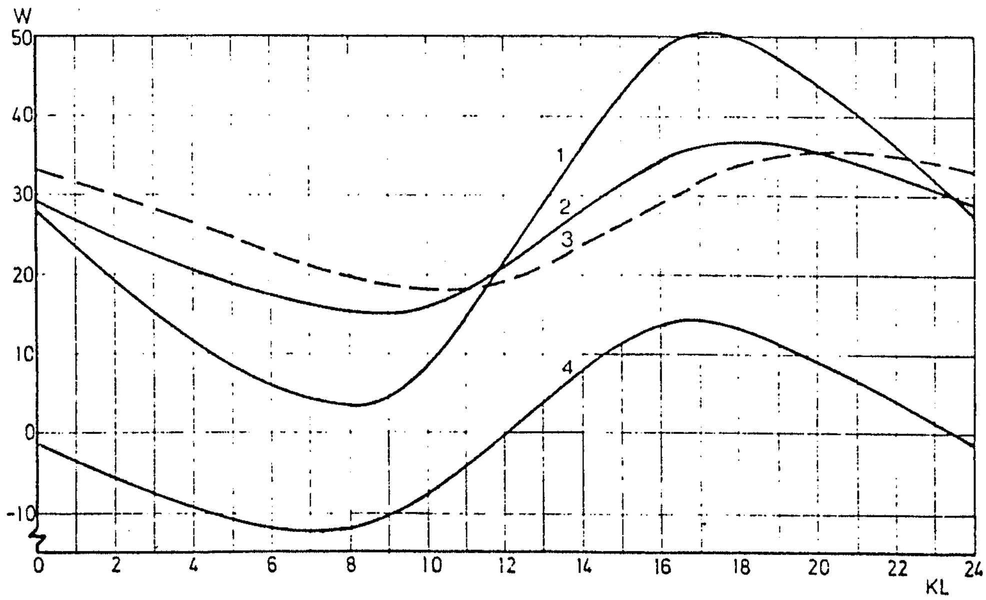


Fig. 9 *Run 4 c. Room with sunlit outer wall. The room air temperature is held constant at 20°C. Requisite output is calculated. Built-up process.*

1. *BRIS Heat flow through outer wall's internal surface.*
2. *BRIS Removed convective effect (cooling requirement).*
3. *BYVOK " " " " "*
4. *BRIS Heat flow through inner-wall and beam surfaces.*

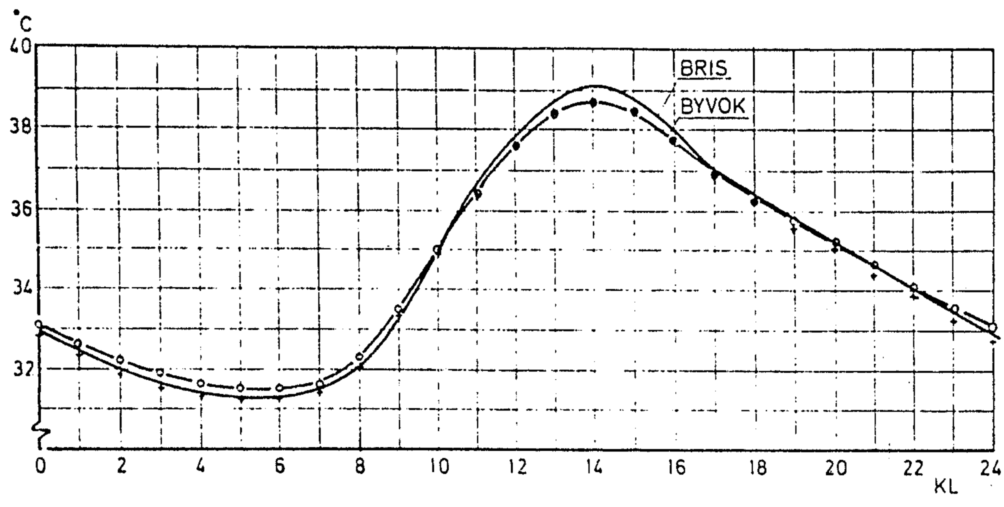


Fig. 10 *Run 5. Room with outer wall and window. Built-up process.*
++ BYVOK with $\alpha_k = 2.5\ W/m^2, K$.

Evaluation of the results

Even though the differences in the results from BRIS and BYVOK cannot be wholly ignored, they are so small as to justify concluding that the programs show very good congruence. However, the convective heat transfer coefficients represent an unclear point.

The fact that the programs yield identical mean values must be considered important. It indicates that the energy balance during the calculation period is correct. Differences can especially arise on this score if the window is not treated in a relevant manner. It will be seen from Appendix C that the equations each program uses to describe the window´s heat balance evince great similarities. Further, we know that the distribution of solar radiation in the room is similarly calculated in both programs and that only an insignificant difference lies in the treatment of the long-wave radiation exchange. Even though the non-stationary heat flows in the walls have not been directly compared, the observations made indicate that BYVOK´s response factor method and BRIS´ difference method provide good congruence.

It should be emphasized that this good congruence of the results was not achieved until the input data were comprehensively harmonized. For this purpose a standardization procedure should be adopted.

4. CONCLUSIONS AND RECOMMENDATIONS

When programs are to be run on computer to calculate indoor climate and effect requirements for climatizing, it is customary for the user himself to determine many important parameters. The implications of this practice became evidently manifest when the initial runs were made. A careful coordination of input data is therefore necessary in comparisons of the kind that were carried out here. Moreover, certain assumptions are built into the calculation models on which the programs are based. If the cause of any differences in results is to be revealable, these assumptions must be amenable to explicit comparison. The Appendix shows the algorithms for calculation of insolation and heat transfer coefficients that are used in the different programs.

The original objective, to harmonize the programs for use in the standardizing work, seems to be fulfilled. The results from the comparisons of BRIS-BYVOK and BRIS- HEAT deviate negligibly in the runs that were made.

An unclear point is how to choose the convective heat transfer coefficients. That choice bears crucially on the results.

In order to fulfil a more general objective further studies will be necessary. Several combinations of building structures, window sizes, sunshades, climatic conditions, installations, operating cycles, etc., will have to be run through. Further, heating and cooling requirements with respect to the formulation of indoor climate criteria should be studied. The computer-run examples are no more than the beginning of a more comprehensive analysis, but for the time being they should still be able to serve as benchmarks for purposes of passing judgment on different calculation methods.

Input data should be of foundation-laying character. Derived magnitudes (e.g. accumulation factors) should not be permitted. All input data should be clearly evident from the printout. Even if the program does not normally generate climatic data, a read-in facility should be provided. Hourly values for climatic data on magnetic tape are becoming more and more accessible. For the future one can well think of making comparisons with real climatic data from some suitably chosen test year.

The calculations should be verified by measurements. Experiences from such trials show that it is very hard to control all factors even if one uses large-scale measuring equipment. Measurements of a simple house model -- a cube with an edge side 1 meter long -- have been performed by the Department of Heating and Ventilating Engineering at the Institute of Technology in Stockholm. The cube lacks windows and the walls are of concrete. Insolation on the cube's walls and roof (5 directions) and some 50 temperatures have been recorded. In spite of this the measurement values did not contain sufficient information from the beginning. Not until after several amplifications were made did it become feasible to do a careful analysis and perform comparisons with the BRIS program. The result was very satisfactory and will be published in a separate report.

APPENDIX: Documentation of certain algorithms

A. Calculation of heat transfer coefficients in rooms

1. Convection (unit $W/m^2, K$)

Program	Vertical surfaces	Floor	Roof
BRIS	$1.88 \cdot \lvert\Delta t\rvert^{0,32}$	$- 2,42 \cdot \lvert\Delta t\rvert^{0,31}$ - in stable layering[1] : 0,6	
BYVOK[2]	4.0	5.0	2.5
HEAT	- - - $1,7 + \lvert\Delta t\rvert^{0,425}$ - - - - - - - - - - - -		

1) Stable layering is assumed to supervene when the roof is warmer or the floor colder than the room air.

2) The heat transfer coefficients in BYVOK are input data and may be freely chosen. The stated values are ordinarily used.

2. Long-wave radiation

BRIS uses Stephan-Boltzman's law and assumes that the room surfaces do not reflect long-wave radiation.

BYVOK has need for linearizing the calculation and also assumes that there are small temperature differentials between those surfaces which exchange radiation. The algorithm for determining the exchange of radiation between two surfaces may then be written

$$q_{i-j} = \frac{1}{25} \cdot \varepsilon_i \cdot C_s \left(\frac{T_m}{100}\right)^3 \cdot \phi_{i-j} \cdot (T_i - T_j)$$

T_m here is the main value of temperatures for the surfaces. The value is estimated beforehand and given in input data.

HEAT uses a constant value, 5.2 W/m^2 K, of the heat transfer coefficient for long-wave radiation.

3. Short-wave radiation

BRIS and BYVOK make allowance for an infinite number of reflections in the room from insolation by using so-called distribution coefficients. These assume that the radiation is diffuse and is figured out of a linear equation system.

The following assumptions are made in HEAT:

- the short-wave solar radiation strikes only floor and furniture surfaces, where it is evenly distributed;
- the illumination´s short-wave radiation is evenly distributed on the floor, furniture and wall surfaces.

Next, the first relection onto other room surfaces is calculated.

B. Calculation of the solar radiation

The three programs calculate the sun´s position in the sky by means of known solid geometry laws. Certain differences may appear due to approximations in those expressions which calculate declination and equation of time. Mathematical expressions for determination of solar and celestial radiation which the programs use are described below.

BRIS

uses expressions based on Lunelund´s measurement values, divided up into summer and winter. For solar altitudes higher than 15° the expressions read:

October - April:

$I_{DN} = 1071 \cdot \exp(-0.109/\sin h)$

May - September:

$I_{DN} = 1071 \cdot \exp(-0.139/\sin h)$

I_{DN} designates the direct solar radiation at right angles to its direction.

For solar altitudes under 15° polynomials are used which connect with the above expressions.

The direct radiation's vertical component is obtained from

$I_{DV} = I_{DN} \cdot \cos i$

where i designates the angle of incidence.

The celestial radiation falling on a horizontal surface is calculated as a function of solar altitude from the following expression:

$$I_{dH} = \begin{cases} -.823 + h\,(5.263 + h\,(-.094 + .0006\,h)) & \text{when } h \leq 60^{\circ} \\ \frac{h - 60}{30}\,(110 - 107.15) + 107.15 & \text{when } h > 60^{\circ} \end{cases}$$

The celestial radiation is assumed to be strongest in the vicinity of the sun. Its vertical component will therefore depend on the sun's position:

$$I_{dV}/I_{dH} = \begin{cases} .45 & \text{when } \cos i \leq -.2 \\ .55 + .437\cos i + .313\cos^2 i\ \mathrm{sign}(\cos i) & \text{when } \cos i > -.2 \end{cases}$$

The ground radiation is calculated on the assumption that the horizon is free and that the ground surface is diffusely reflecting:

$I_{ground} = \frac{1}{2} \cdot r_{ground} \cdot I_H$

After the various components of insolation on the façade have been thus calculated, the next step is to determine the radiation that is transmitted through a reference window (usually a two-pane window). The direct component is reduced according to a transmission curve which depends on the angle of incidence. It is described by the following algorithm:

$X = \cos i$

$$T_{ref} = \begin{cases} -.105 + X\,(2.821 + X\,(-2.998 + 1.071\,X)) & \text{when } 0 < i \leq 75^{\circ} \\ 1.80\,X - .028 & \text{when } 75 < i \leq 85 \\ 1.48\,X & \text{when } i > 85 \end{cases}$$

Where incidence is perpendicular, $T_{ref} = .789$. Diffuse radiation is transmitted to 67 %.

These values are to be multiplied by shading coefficients, whose values for some ordinary combinations of glass and sunshade are stated in various sources including the user specifications. (A more complete body of materials is to be found in Building Research Report No. R 19:74.)

BYVOK

The direction of the sun´s direct radiation intensity is normally expressed as:

$$I_{DN} = I \,.\, e^{-A/\sin h}$$

Based on Lunelund´s measurements the following values are set:

$I = 1070\ \mathrm{W/m^2}$

h = solar altitude

$$A = \begin{cases} 0.1 & \text{when } 51 < DAG < 344 \\ 0.1 + \frac{0.04}{119}\,(DAG - 52) & \text{when } 51 > DAG > 171 \\ 0.14 & \text{when } 171 > DAG > 232 \\ 0.14 - \frac{0.04}{111}(DAG - 232) & \text{when } 232 > DAG > 344 \end{cases}$$

DAG is the number of the day (1 to 365).

Against a vertical surface the intensity is given by:

$$I_{DV} = I_{DN} \cdot \cos\theta$$

θ = the sunray´s angle of incidence on the surface

The celestial radiation falling on a horizontal surface is derived from:

$$I_{dH} = 0.1 \cdot I_{DN}$$

Against a vertical surface the diffuse radiation is a function of the sun´s position determined by the angle of incidence:

$$I_{dV} = I_{dH} \cdot f\,(\cos\theta)$$

$$f(\cos\theta) = \begin{cases} 0.45 & \text{when } \cos\theta < -0.2 \\ 0.55 + 0.437.\cos\theta + 0.313\cos^2\theta & \text{when } \cos\theta > -0.2 \end{cases}$$

The calculation of ground-reflected radiation assumes a free horizon and diffuse reflection so that the diffuse radiation falling on a vertical surface acquires an added component:

$$I_{ground} = \frac{1}{2} \cdot r \cdot (I_{dH} + I_{DN} \cdot \cos\theta')$$

Cloudy days can also be calculated. Here use is made of the formulas employing empirical constants as set out in:

Kimura, Stephenson : Solar Radiation on Cloudy Days.
ASHRAE Transactions 1969, Part I.

In making calculations of solar data the time equation can be borne in mind, which means that both normal time and true solar time can be chosen as time parameters.

<u>HEAT</u>

The calculation of solar radiation falling on the building´s outside surfaces is determined by measurements of direct and diffuse radiation intensities against a horizontal surface. The program reads these and related values of the sun´s position by the hour. For normal cases permanent weather files are available for six towns in Finland. The measured climatic data break down into clear and cloudy type days during winter and summer. Since every town uses its own observation material, the climatic data already contain the correction between normal time and solar time.

Climatic data are stated by other means in exceptional cases. In these instances the radiation values are ordinarily based on Lunelund´s measurements or on technical manuals.

The direct radiation intensity I_{DV} against vertical surfaces is calculated in the program with the formula

$$I_{DV} = I_{DH} \cos i / \sin h$$

where

I_{DH} = direct radiation on a horizontal surface

I = angle of incidence

h = the sun´s angle of elevation

The diffuse radiation falling on a vertical surface is assumed to be half of the diffuse radiation on the horisontal plane.

For purpose of calculating the radiation I_{mv}, that is reflected from the ground surface, it is assumed that the reflection complies with the cosine emission law and that the horizon is free, which gives rise to

$$I_{mv} = 0{,}5\ r_m\ (I_{DH} + I_{dH})$$

where

r_m is the ground surface´s reflection factor

I_{dH} is the diffuse radiation on the ground surface.

C. The window's heat balance

BRIS

The window is regarded in the program as a disc without thermal capacity but with a given (constant or varying) heat resistance from the inner surface to the outdoor air and similarly given values for direct transmission and absorption of short-wave radiation. The figure below shows the appearance of the model.

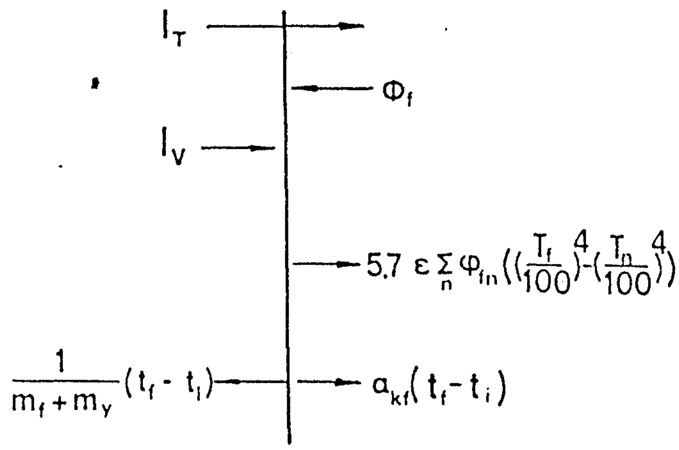


Fig. C:1

It contains, first, the given magnitudes

I_T directly transmitted short-wave radiation

I_v absorbed ditto

$m_f + m_y$ heat resistance from inner surface to ambient temperature

ϕ_f reflected-back short-wave radiation, as well as any such radiation falling in from other windows, which is absorbed by the window[1])

second, the component variables of the system

t_f temperature on the inside of the window

t_n (different) temperatures of other room surfaces

1) ϕ_f is calculated in other sections of the program and can therefore be considered given from the window's viewpoint.

t_r room air temperature

Where there is only one window, then

$$\phi_f = I_T \psi_{ff}$$

where ψ_{ff} designates the distribution coefficient for radiation from the window surface to the window itself. Otherwise I_T does not enter into the window's heat balance but is distributed to the other room surfaces in proportion to the distribution coefficients.

Input data present the given magnitudes in an easily recognizable form, namely as insolation through a reference window (I_{ref}), shading coefficients for direct (F_2) and total (F_1) transmission, and k-value.

I_{ref} is normally generated by the program but may also be given in table form.

The directly transmitted solar radiation is obtained from

$$I_T = F_2 \cdot I_{ref}$$

and the heat resistance

$$m_y + m_f = 1/k - m_i$$

where m_i is a standard value for the heat resistance at the inside of the window. This standard value also enters into the assumptions for calculating F_1 and must be excised. This is done in line with the following equation:

$$I_V = \frac{F_1 - F_2}{1 - m_i \cdot k} \cdot I_{ref}$$

It is assumed in the program that m_i = 0.11 m2 K/W

BYVOK

Heat resistances

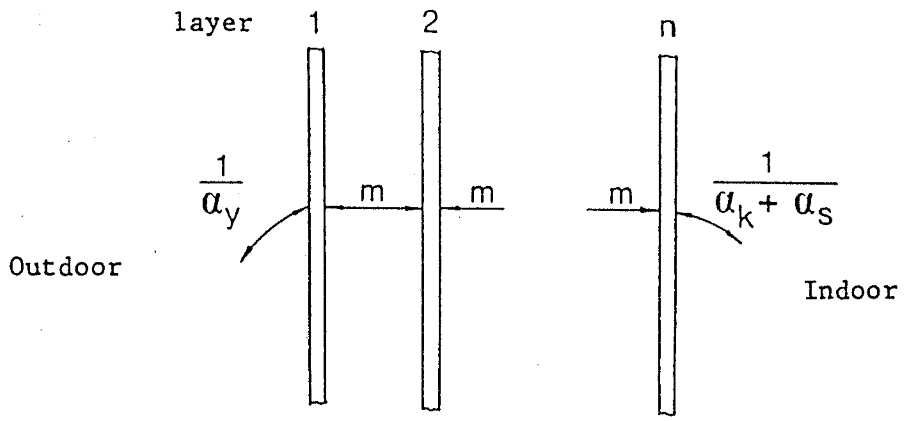


Fig. C:2

All that is regarded from the room is in the inner layer in the window. The resistances from the inner surface and out are simply calculated from

$$m' = \frac{1}{\alpha_y} + m(n - 1)$$

where n = number of layers in the window

α_y and m are input data

Inner heat transfer coefficients are divided between convection (α-value = constant = input data) and long-wave radiation. The radiation heat transfer coefficient is calculated contingent upon emission factor and average radiation temperature.

Insolation

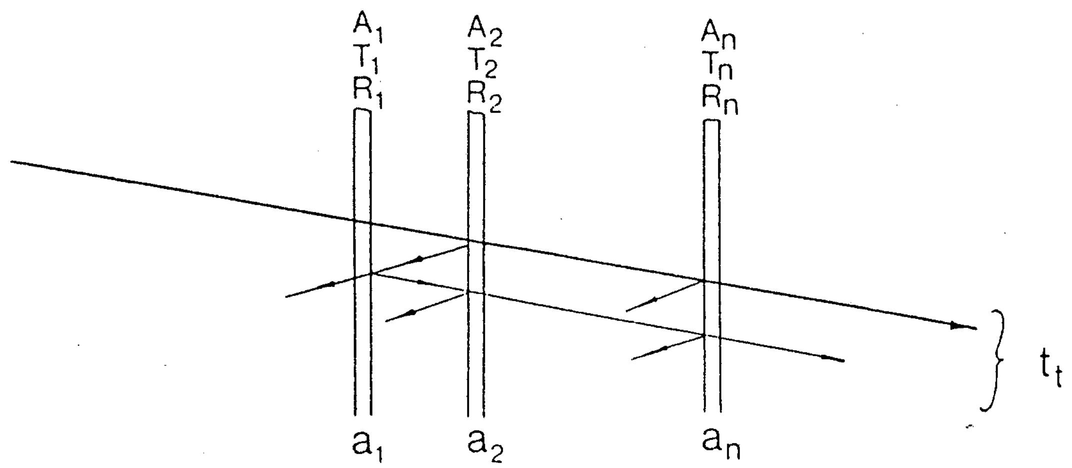


Fig. C:3

A, T and R are to be specified for all layers where incidence is normal. The next step is to calculate the direct transmission t_t and the absorption in each layer a_1, a_2 .... a_n.

Allowance is also made for the influence of the angle of incidence. The single-pane window $t_{ref}(\theta)$ is used as reference (acc. to ASHRAE).

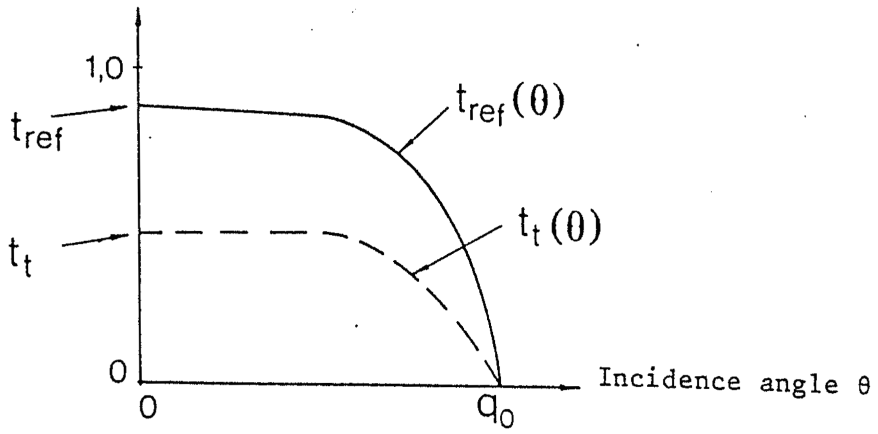


Fig. C:4

Next, the window solution under consideration is adjusted for the angular dependence:

$$t_t\ (\theta) = t_{ref}\ (\theta) \cdot \frac{t_t}{t_{ref}}$$

This angular dependence holds only for direct solar radiation. For the diffuse type the transmission conditions hold at about 60° if one assumes an evenly shining sky.

The absorbed solar radiation is also adjusted for dependence on the angle of incidence by analogy with the direct radiation.

<u>Secondary heat flow</u>

Once the room's heat balance is established it becomes advantageous to regard the window as one layer. For the inner layer one can determine the "total absorption effect" from the equation:

$$a_n' = \sum_{i=1}^{n} a_i \cdot mu_i / m'$$

mu_i = resistances from layer in and out.

The reflected-back short-wave radiation is also to be taken into account for the inner layer. The size of this radiation is fixed when the distribution of solar radiation is calculated. For this purpose the reflection factor to be used is calculated together with the other optical properties of the window. Used here as absorption factor is a_n.

The heat balance for the window thereupon takes on the following appearance:

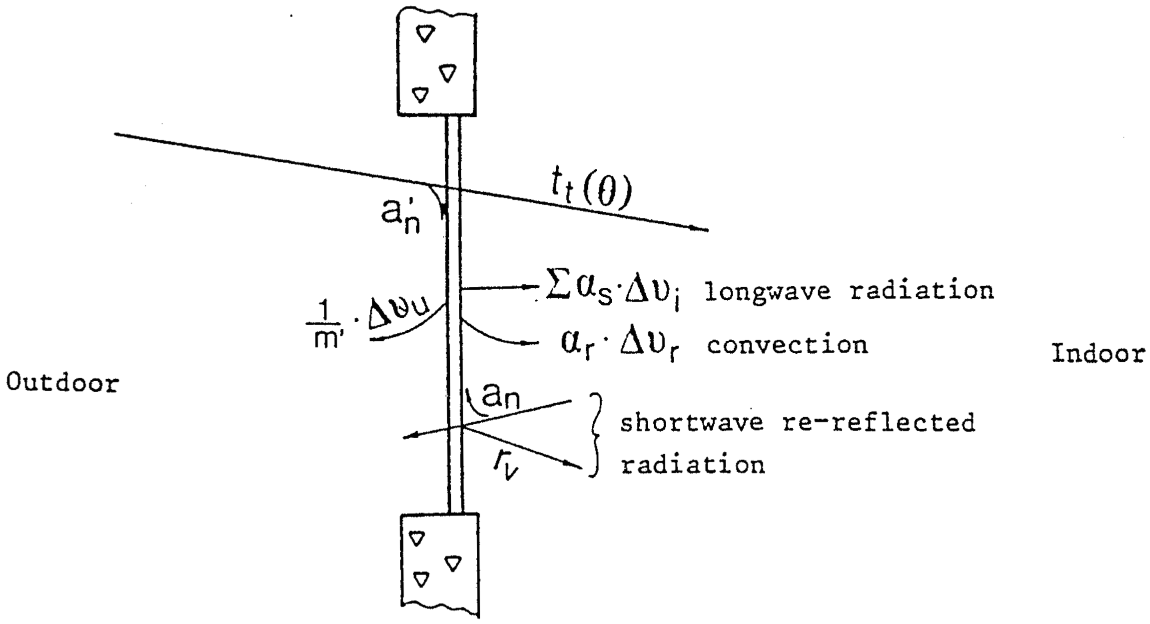


Fig. C:5

HEAT

The window's transmission and absorption in different layers are obtained by means of series development, Fig. C:3. Transmission of the direct radiation depends on the angle of incidence, see e.g. Fig. C:4. Transmission and absorption data for the diffuse and reflecting radiation are assumed to be the same as for perpendicular insolation. This program contains some of the most common optical properties of window layers as functions of the angle of incidence. These layers are

- ordinary 3 mm factory glass
- absorbing 5 mm glass
- reflecting 5 mm glass (Ni)
- Venetian blind, slat angle 45^o, the ratio of slat width to step height being 1:1,2.

Combinations of these layers give rise to the window designs that are in most general use. Data for other layers may be inserted in the program.