The Main Trends in Energy Saving in Buildings — Theory and Practice in the U.S.S.R.

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SUMMARY

The paper reviews some problems of theory and practice of energy conservation in buildings. The necessity for a policy of energy saving in the country is substantiated. The problems of energy conservation are studied in terms of mathematical simulation of a building as a single energy-consuming system. The method is given of economic optimization of the total thermal resistance value of the envelope, which is the basis of the Soviet Building Code on Heat Engineering. The Soviet Code provisions are compared with those of other countries. Some ideas on optimization of window structures are presented.

INTRODUCTION

Global building and construction accounts for 37% of the total world primary energy consumption. The major part of that energy is used to provide comfortable conditions, to heat and cool indoor air, ventilation, hot water supply and lighting. In the U.S.S.R., 370 million tonnes of conventional fuel (coal equivalent) is spent annually for these purposes, or about 25% of total national energy consumption. The total housing stock of the country is 4.3 billion m^2 of the total area, but the volume of houses and public buildings exceeds 20 billion m^3. Annual energy consumption in residential and public buildings takes 250 million tonnes of coal equivalent (TCE). Of the total heat demand in the country, an average of 55% (70% in the towns) is met by centralized sources, 39% by thermoelectric plants, and 16% by district heating systems. About 75% of energy is consumed by heating, ventilation and hot water supply, 17% by lighting and electric motors. An annual rise in energy consumption of about 6.5 - 7 million TCE (0.2 EJ) is observed as a result of new buildings put into operation. Walls of new residential buildings in cites are built mainly of prefabricated panels (70%), and 30% of brick. 70% of panel production constitute single-layer panels of lightweight concrete as compared to laminated panels with an efficient insulation material. The 27th Congress of the Communist Party of the Soviet Union (CPSU) has set a goal of satisfying the rising demands of the national economy mainly by resource conservation. In the next five years, it is necessary to achieve conservation of 200 - 230 million TCE, 10 - 12% of cement, 12 - 14% of wooden materials and 14 - 16% of ferrous metals. It is expected that up to 60 - 65% of demands for fuel, energy and raw materials will be satisfied by savings.

The challenge, therefore, is to improve the energy efficiency of buildings under construction without substantially increasing the consumption of building materials. The effective use of energy implies a decrease of energy consumption with no loss in environmental, thermal and lighting comfort and quality.

Heat engineering design in the U.S.S.R. 10 - 15 years ago, sought only to meet sanitary and hygienic requirements minimizing the cost of construction. Today, such design takes into account not only sanitary and hygienic requirements and construction cost but also the cost of running the building, i.e., energy expenses. The latter problem requires a deeper understanding of the laws of building physics [1 - 3].

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The objectives of our research work on energy conservation in buildings include:
— reducing heat losses through the building envelope;
— increasing the efficiency of the heating and ventilation systems;
— providing the required lighting with minimum energy expense;
— using non-traditional energy resources for heating buildings.

A survey of some research work is given below.

THE BUILDING AS A SINGLE ENERGY-CONSUMING SYSTEM

The objectives of providing environmental, thermal and lighting comfort are closely interrelated. The building can, therefore, be regarded as a single energy-consuming system with a variety of elements where various physical processes of energy absorption, transformation and transfer occur. To find the parameters which are the most important for energy consumption and to arrive at optimum solutions, mathematical models are used to simulate the thermal performance of buildings over an annual operating cycle. Below, mathematical models of indoor thermal conditions will be considered. The method is given in detail in ref. 2.

When developing mathematical models, the systems approach:
— singles out the buildings in question from the whole energy-consuming system, e.g., a residential district, a workshop at a plant, etc.;
— identifies elements which compose the building, their internal structures and types of interrelations;
— divides the building into simpler elements by the decomposition method and restores it with the help of the graph theory;
— works out a system of interconnected mathematical models of individual building elements and unites these models into a single mathematical model.

The following major parameters are chosen to characterize the building as a single energy-consuming system: a set of parameters of the outdoor weather, radiant and convective heat exchange between the outdoor weather and the building, heat and mass transfer through the building envelope, thermal inertia of the building envelope and equipment, heat gains from the heating systems in the building, and heat losses due to air exchange. A balance equation helps to unite all the models into a single one.

The system of elements and relationships simulating the indoor thermal conditions can be presented in the form of a graph where each vertex of the graph corresponds to an element of the room and each arc of the graph corresponds to a relationship between two indoor elements or between an element indoors and an outside element. Figure 1 presents a simplified scheme for the heat balance of a room which includes an outside wall, an inner wall and a window. Figure 2 presents a corresponding graph. The vertices are joined by two arcs because two means of energy transfer are used. Thus the matrix of connections between the vertices of the graph is established.

Such a mathematical model of the heat balance of a whole building involves a great number of coupled differential equations and is very difficult to solve. For instance, the system of equations describing the heat balance of a modern dwelling of 100 apartments must be replaced by a system of a million finite-difference equations. However, by combining finite difference equations it is possible to exclude a great number of unknowns and

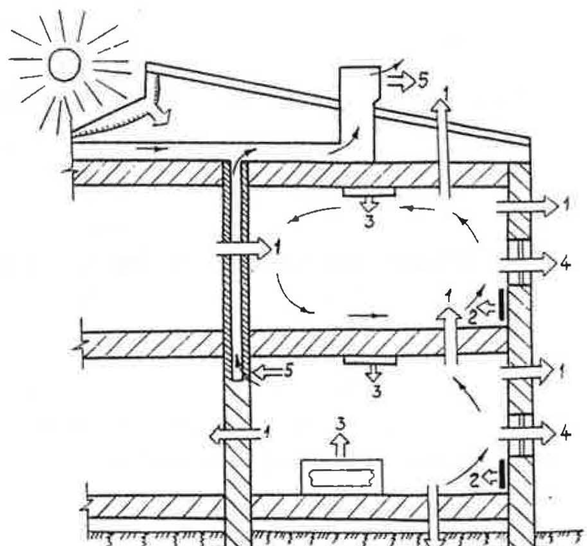

Fig. 1. Scheme of the indoor thermal balance of a building. 1, Heat losses and heat gains through the enveloping structures (walls, roofs, floors); 2, heat gains from the heating devices; 3, heat gains from the technological equipment; 4, heat losses through the window; 5, heat losses due to air exchange.

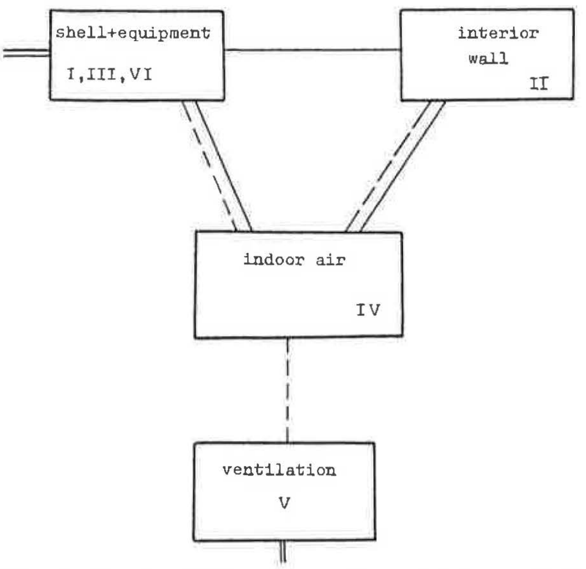

Fig. 2. Graph of the indoor thermal balance. I, II ... VI are vertices of the graph corresponding to each element of the room (in Fig. 1) of the building as a single energy-consuming system; arcs of the graph — — - convective links, —— radiative links; ═══ outside links.

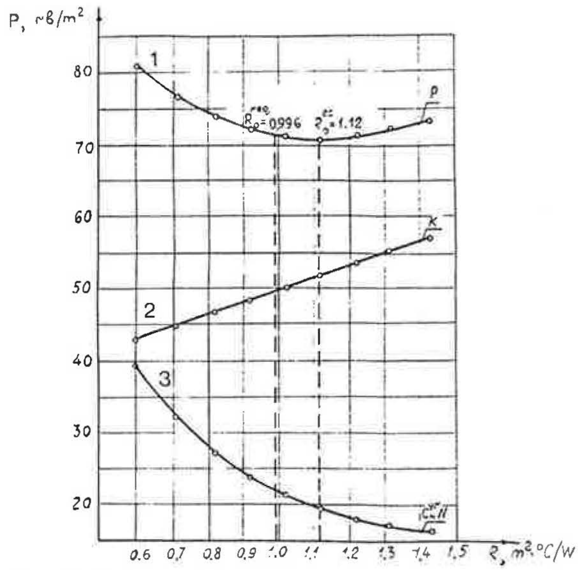

Fig. 3. Relationship of the reduced cost versus the total thermal resistance. Curve 1 is the sum of capital investments and operating costs related to 1 m^2 of the envelope; curve 2 indicates the first capital cost related to 1 m^2 of the envelope; curve 3 gives the cost of heating related to 1 m^2 of the envelope.

to reduce the solution of the problem to a limited set of equations.

Programs based on such mathematical models can simulate thermal behaviour of a building for a day, a week, a month, or a year. Such models make it possible to solve the main problem of thermal analysis of buildings, which is to find the optimal relationship between the capacity of the heating (cooling) system and the thermal properties of the envelope.

ENERGY-RELATED BUILDINGS CODES

The problem of reducing heat losses through the building envelope is quite complex. The National 1986 Code of the U.S.S.R. stipulates not only design requirements but also calculation methods.

According to the Soviet Building Code *Heat Engineering* [4], the thermal properties of the building envelope (walls, windows, etc.) are determined in terms of the economically optimal reduced thermal resistance R_o^{ec}, defined as the minimum reduced cost involving the envelope cost expenses, the cost of heating the buildings, the capital investment payback, etc. Sanitary and hygienic requirements are constraints. The economic parameter for definition of economically optimal thermal resistance is the minimum value of the reduced cost (Fig. 3).

Figure 3 shows the essence of the process of minimization: curve 1, the total reduced cost is the sum of capital investments and operating costs related to 1 m^2 of the envelope in roubles per square metre (rbls/m^2); curve 2, the first capital cost related to 1 m^2 of the envelope (rbls/m^2); curve 3, the cost of heating related to 1 m^2 of the envelope (rbls/m^2). By increasing the total thermal resistance R of the envelope, the cost of heating will reduce (see curve 3), but the first cost of the envelope will increase (see curve 2). As a result, the place on curve 1, corresponding to the minimum total reduced cost defines the optimal total thermal resistance value of the enveloping structure.

The above principle can be written in the form of the formula:

$$P = K + C_h^{yr} N \qquad (1)$$

where

P = reduced costs for the lifetime of the enveloping structure (rbls/m^2)

K = the first capital cost of construction, including the cost of production, transportation and assembly (rbls/m^2)

C_h^{yr} = annual expenses of heating (rbls/m^2 yr)

N = the coefficient for reducing the expenses incurred (year).

The coefficient for reducing the expenses, N, at various times to the expenses of the year when the envelope was constructed is required because expenses of future years are not realized that year and they can be used for other purposes and, therefore, be partially returned due to profit. According to the current Soviet Code the coefficient is $N = 12.5$ years. The Building Code on Heat Engineering [4] gives a more detailed formula:

$$P = K + \frac{3.6 \times 10^{-6}(t_{in} - t_{ht})Z_{ht}m}{R} C_T l_T N \quad (2)$$

where

t_{in} = the design indoor air temperature (°C)
t_{ht}, Z_{ht} = the average temperature (°C) and duration of the heating period (h/year)
m = the coefficient taking into account additional heat losses due to infiltration
R = the reduced total thermal resistance of the enveloping structure (m^2 °C/W)
C_T = the cost of heat energy (rbls/GJ)
l_T = the coefficient taking into account the change in the heat energy cost in time (escalation rate)
3.6×10^{-6} = a normalizing coefficient.

Other symbols are the same as in eqn. (1).

The reduced total thermal resistance R is estimated with account taken of thermal bridges. Equation (2) is valid for all types of enveloping structures, including walls, floors, windows, etc., and does not depend upon the height of the building.

The fractional expression on the right-hand side of eqn. (2) is an annual consumption of heat energy by heating the envelope. The product $(t_{in} - t_{ht})Z_{ht}$ is heating degree-hours and it defines various climatic zones of the country. Values for typical regions of the country vary from 50 000 degree-hours for Tashkent, 110 000 for Moscow, to 280 000 for Verkhoyansk. When estimating the value, it is assumed that the heating season starts when the mean diurnal outdoor air temperature goes below 8 °C for residential buildings and 10 °C for hospitals, kindergartens and other similar buildings.

As seen from eqn. (2), annual heating expenses C_h^{yr} are

$$C_h^{yr} = \frac{(t_{in} - t_{ht})Z_{ht}m}{R} C_T l_T \quad (3)$$

Heating expenses C_h for the structure's lifetime, i.e. expenses of future years, are reduced to expenses of the current year by the geometric progression formula:

$$C_h = \frac{C_h^{yr}}{1 + 1/N} + \frac{C_h^{yr}}{(1 + 1/N)^2} + \ldots + \frac{C_h^{yr}}{(1 + 1/N)^y} \quad (4)$$

where y = the structure's lifetime (yr). For a long lifetime (70 yr and more), using the formula of the diminishing progression sum and neglecting the multipliers of small magnitude, eqn. (4) is written in the form $C_h = C_h^{yr}N$, i.e., as it is given in eqns. (1) and (2).

According to the Soviet Code, it is obligatory to compare a few types of enveloping structures and to choose that structure with the largest reduced cost.

According to the current list of prices, the cost of thermal insulating material (to be included in K) is nonlinearly related to the thickness of insulation. In this connection, the economically optimal total thermal resistance could not be found under conditions $dP/dR_o = 0$. So R_o^{ec} values are calculated for different variants on the condition of minimum P value. The economically optimal total thermal resistance is, as a rule, higher than the required thermal resistance R_o^{zeq} specified in the rules based on sanitary and hygienic requirements, with the exception of some industrial buildings which have high relative humidity (80 - 95%) and relatively low indoor air temperature (2 - 6 °C).

Currently the Code-stipulated reduced total thermal resistance of the building envelope (excluding fenestration) varies from 0.54 m^2 °C/W in the southern part of the U.S.S.R. to 3.9 m^2 °C/W in the northern area.

Table 1 gives the Code provisions of the U.S.S.R. and some other countries.

Air permeability of buildings is very important for heat losses of the building. The current Code-stipulated air permeability for external walls is 0.5 kg/m^{2}h, for joints 0.5 kg/m^{2}h, for entrance doors 1.5 kg/m^{2}h. The air permeability of windows and balcony doors depends on the mean temperature of the coldest five days, at −40 °C and below it is equal to 8 kg/m^{2}h, in other cases 10 kg/m^{2}h (for the pressure difference of 10 Pa). In Sweden, the air permeability for walls varies from 0.25 to 0.6 kg/m^{2}h, and for windows and doors 2.4 kg/m^{2}h (for 50 Pa) and 8 kg/

TABLE 1

Country, title of Standard, year of issue	Code-stipulated total thermal resistance of enveloping structures of buildings (m^2 °C/W)									
	Walls	Covering and roof	Floors: On the ground	Floors: Over the cellar	Floors: Over the basement	Windows	Biggest window area (%)	Doors	Reduced total thermal resistance	
USSR, SNiP II-3-79xx, 1986	0.54 - 2.9	0.85 - 3.9	—	0.3 - 1.7	0.5 - 2.8	0.18 - 0.55	—	0.32 - 1.74	—	
Denmark, BB77, 1979	2.5 - 3.3	5.0	3.3	3.3	2.5	0.34	15	1.05	—	
Sweden, SBN 1980	3.3 - 4	5 - 5.9	3.3	3.3	2	0.5	15	1.0	—	
Finland, C3, 1985	3.57	2.2 - 4.55	2.2 - 2.78	2.2 - 4.55	—	0.32 - 0.48	15	1.43	1.67	
United Kingdom, BS81, 1985	1.42 - 1.67	1.67 - 2.86	—	1.42 - 1.67	—	—	12, 15	—	—	
The Netherlands, NEN1068, 1981	1.28	1.28	0.52	0.52	0.52	0.36	—	—	0.5 - 1.1 0.71 - 1.2 0.83 - 1.67	level b level c level d
Switzerland, SIA180, 1980	1.67	2	1.25	1.67	1.25	0.3	—	—	1.33 - 1.67	
FRG, DIN 4108 with supplements, 1987	1.25 - 2	—	1.1	2.2	1.25	0.28	—	—	0.54	
Norway, NS, 1980	1.25 - 3.3	1.67 - 5	3.3	3.3	3.7	0.41	15	0.5	—	
Canada, NRC, 1978	2.5 - 3.7	2.5 - 7.14	2.5 - 4.76	2.5 - 4.76	2.5 - 4.76	0.35 - 0.45	15	1.43	—	
USA, Standard 90 (90.1P, 90.2P), 1985	1.08 - 2.5	3.57 - 7.14	—	—	—	0.49	—	—	—	
GDR, TGL35424, 1981	0.75 - 1.5	—	—	—	—	—	—	—	—	
PPR, PN-82/B, 1982	0.71 - 1.33	0.83 - 2.5	1.1 - 1.67	1	—	0.17 - 0.5	—	—	0.81 - 1.63	
ČSSR, ČSN 73054, 1979	0.95 - 1.1	1.8 - 2.15	0.75 - 1.1	0.86 - 1.05	0.65 - 0.99	0.27	—	0.21	—	

[a]Heat protection levels estimated taking into account economic matters: level b is the existing rated level; level c is the perspective level; level d is the ultimately possible level without serious changes in the enveloping structures.

m^2h (for 500 Pa). It is sometimes necessary to analyse the thermal performance of the building for an annual cycle and to determine the amount of heat Q_T needed for heating the building during the cold period and the amount of cold Q_X to cool the building in the warm period. The task of minimization of energy consumption in the building consists of finding out the minimum of the reduced costs P of the enclosing structures for an annual cycle:

$$P = K + C_T^T Q_T N + C_T^X Q_X N \quad (5)$$

where K and N are the same as in eqn. (1), and C_T^T and C_T^X are the energy costs for the heating and cooling of the building respectively.

WINDOWS

Windows with single panes are used only in certain regions of the U.S.S.R. In the regions where the design temperature is −31 °C or less (instead of the former design temperature of −41 °C), triple glazing is used. The window area is restricted to about 15% of the wall area of the living rooms and kitchen. In other countries similar solutions are found: the window area is restricted to 15% of the floor area in the Danish and Swedish Codes, and according to the British Code the percentage is restricted to 25% for civil buildings and to 15% for industrial buildings.

In the U.S.S.R. the Code-stipulated temperature on the internal side of glazing and casement should not be less than 0 °C. The optimal value of the indoor air temperature in winter in residential and public buildings should be 18 - 20 °C, while in industrial buildings it should be 16 - 20 °C. The air flow rate in residential and public buildings should not exceed 0.1 - 0.15 m/s, and in industrial buildings 0.2 - 0.3 m/s.

Complex methods of optimization have been developed to specify how transparent enclosing structures should provide an appropriate microclimate and daylighting level with minimal heat loss and construction and running cost. The required light, thermal and air microclimate indoors can be provided with various numbers of panes and areas of glazing, with different structures of windows, with daylighting and combined lighting, with and without heaters under windows, etc.

A window efficiency coefficient K_{ef} [5] is introduced which compares the heat loss through a window to the heat loss through a reference window with single glazing (R_o^{ec} = 0.16 m^2 °C/W) and compares the light transmission to its largest achievable factor (τ_o^{ref} = 0.9):

$$K_{ef} = \frac{R_o^{ref}\tau_o^{ref}}{R_o\tau_o} = \frac{0.144}{R_o\tau_o} \quad (6)$$

A calculation of typical window structures was made for Moscow climatic conditions. The most effective appeared to be a triple-pane unit (a two-pane unit and a single pane): R_o^{ref} = 0.53 m^2 °C/W, τ_o = 0.36, K_{ef} = 0.75, allowing 9 kg CE/m^2 yr (260 MJ/m^2 yr). The heat losses of such a window will be about 47% less than those of a single window or 30% less than those of a double one.

Calculations of natural convection show that in dwellings, unless heating devices are placed under windows, the air velocity at a distance of one metre from the window and nearer will be above the rated value of 0.15 m/s. Such devices increase the annual heat losses by 20% through double glazing and by 10% through triple glazing.

BUILDING AUTOMATION SYSTEM

At present, computerized indoor environment control systems in big industrial and office buildings conserve up to 25 - 30% of the energy required annually for space heating. The system is characterized by two-level control. Microprocessors control heating, ventilation and air-conditioning systems at the lower level and the microprocessor is controlled by the central computer at the upper level.

Energy conservation due to computerized environmental control is achieved as a result of the following procedure. Thermal performance of the building is simulated by a mathematical model which takes into account transmission losses, infiltration, outdoor climatic effects and technological heat gains, and estimates the demand for ventilation, heating and air conditioning; the operating conditions of the heating, ventilation and air-conditioning systems are chosen to balance the running heat loss; transfer conditions are optimized and central control is accomplished.

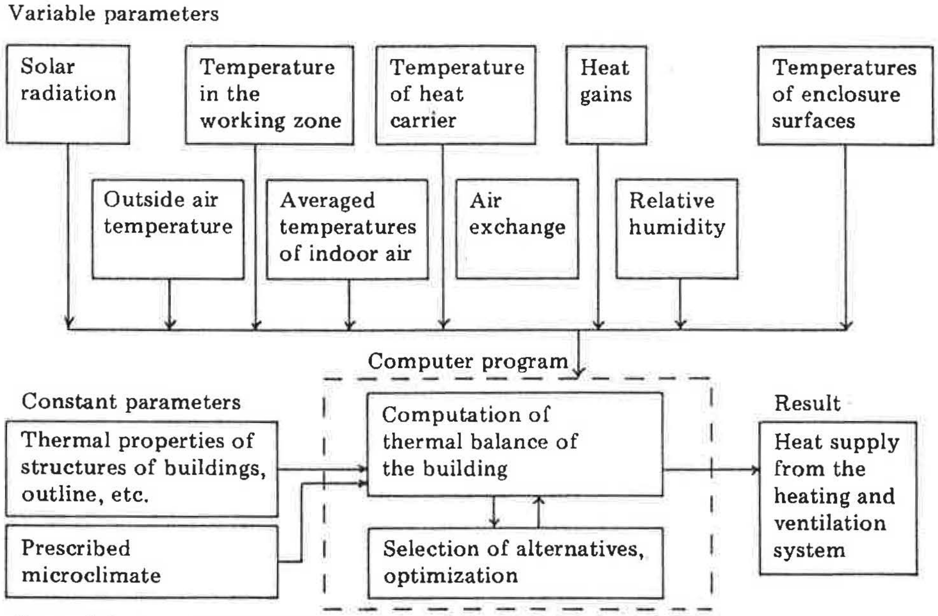

Fig. 4. Scheme of mathematical simulation.

Figure 4 presents the mathematical model scheme. The details for developing specific models are given in ref. 2. The especially developed applied software tackles the following major control problems: optimization of technological parameters of processing the air in systems of heating, ventilation and air conditioning (HVAC) and correction of these parameters and regulation due to the estimated criteria of optimization; control, display and logging of the state of technological parameters of the HVAC system; processing of the analogue and discrete information, regulation and control of technical equipment of the HVAC system. The first two problems are solved by the central computer, the third one by microprocessors.

The mathematical model is a system of heat balance equations [2] defining air exchange, technological heat gains, outdoor climatic effects, heat losses through external enveloping structure due to heat conduction and outdoor air infiltration, heat gains from technical equipment, products and interior structures, processes of heat exchange in the HVAC system.

The economic efficiency of the computer-controlled system of microclimate is defined by the difference of savings due to the system and cost of its development. The annual economic effect E is determined by the formula:

$$E = (P - Z) - nK \qquad (7)$$

where
P = the total cost of energy conserved per year (rbls)
Z = current expenses on maintenance of the system (rbls)
n = the Code-stipulated coefficient of economic efficiency, equal to 0.15
K = capital investments in creating the system (rbls).

For instance, if the capital investments in the system are $K = 230\,000$ rbls, including the cost of equipment and its assembly, the current expenses on the system's operation $Z = 30\,000$ rbls, including the wages of the main staff, production heat consumption of the system, etc., the total cost of energy conserved during a year $P = 300\,000$ rbls, then the annual economic effect is $E = 235\,000$ rbls and the return period for capital investment is about one year.

The full savings due to the system's operation during its lifetime of 10 years is 2.3×10^6 rbls.

One of the experimental systems was put into operation in 1981 at a big industrial building of 2.4×10^6 m^3. The building has air heating combined with ventilation. There are 44 intake chambers with radiators of 200 000 m^3/h capacity each. The system establishes a pre-assigned thermal performance by quantitative and qualitative regulation of water supplied to the main pipeline by mixing up colder water from the output pipeline and by controlling heat gains from radiators. Temperature and rate of heating of the mass are computer-regulated by changing the capacity of the water pump, and changing the fan rotation frequency regulating the heat gains from the radiators.

The experience gained shows that the use of such systems in large industrial buildings of 1×10^6 m^3 saves not less than 30% of energy and the payback period is 1 - 1.5 years.

CONCLUSION

This paper has set forth only a few of the efficient ways of achieving energy conservation in buildings and has been limited to a concern only for thermal properties of buildings and daylighting, i.e., aspects of building physics. Substantial energy saving can also be achieved by improving the space-conditioning systems (heating, ventilation and air-conditioning systems) as well as by introducing systems using non-traditional energy sources (sun, soil, wind, etc.), that are not dealt with in this paper.

REFERENCES

1. V. A. Drozdov, V. K. Savin and Yu. P. Aleksandrov, *Heat Exchange in Light-transparent Structures*, Stroiizdat, Moscow, 1979, (in Russian).
2. Yu. A. Tabunshchikov, D. Yu. Khromets and Yu. A. Matrosov, *Thermal performance of the Building Envelope*, Stroiizdat, Moscow, 1986, 380 pp., (in Russian).
3. V. N. Bogoslovsky, *Heat Engineering*, Vysshaya Shkola, Moscow, 1982, 415 pp., (in Russian).
4. *Building Code and Regulations, SNiP II-3-79xx*, *Heat Engineering*, Gosstroy of U.S.S.R., Moscow, 1986, 32 pp., (in Russian).
5. V. K. Savin, Heat engineering, illumination engineering and economics fundamentals for designing windows in buildings erected in the north, *Energy-efficient Buildings, Proc. Soviet-Finnish Seminar, Moscow, 1986*, VNIIS of the U.S.S.R. Gosstroy, Moscow.