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The Operational and Maintenance Specificity of Heating Systems Depending on the Thermal Inertia of Buildings

Viktors Zebergs[1], Namejs Zeltins[2,] , Gita Actina[3], VisvaldisVrublevskis[4],
[1,2,3]Institute of Physical Energetics, [4]Riga Technical University

***Abstract* – The paper formulates the role of thermal inertia of the building materials in the supply of buildings with energy and in solution of the energy efficiency problems. The evolution of construction entails application of new building materials and glazed surfaces in the envelopes of buildings. An analysis of the influence of the thermal resistance of building materials and their heat capacity on the thermal inertia indicators of buildings has been conducted. An inertia scale of buildings has been developed for the choice of the heat supply capacities of buildings at low outdoor temperatures under extreme conditions of the Latvian climate. The ratio of the ventilation capacities has been analysed in the total heating balance at a low thermal inertia of buildings. The significance of innovative ventilation technologies for raising the energy efficiency has been considered.**

Keywords – sustainable buildings, energy efficiency, thermal inertia of buildings

I. Introduction

Under the climatic conditions of Northern Europe, there is great consumption of thermal energy (reaching 60% of the total energy consumption). Climatological analyses show that in some regions (including Latvia) there are prolonged periods with variable and unstable weather conditions (mainly in spring and in autumn). In order to increase the share of the saved energy and lower its cost by attracting the surrounding RES, energy efficiency (EE) measures can be applied.

An essential factor how to increase the amount of the saved energy is the use of the RES. In-depth analysis of the thermal inertia (TI) of buildings shows that there are few investigations regarding how to take into account the RES when estimating the TI of massive buildings and how to increase the TI of modern buildings. As it is evident from climatological data, by using the TI of buildings it is possible to shorten the duration of the heating period by half (by 92 days). Close to the sea such periods may be longer by 10%.

This costs almost nothing in the buildings with great thermal inertia, but the thermal inertia of the houses erected from modern building materials (by optimising the envelope of the buildings) may be increased due to extensive use of the RES of the surrounding area.

In order to ensure sustainable energy efficiency (EE), several evaluation methods of the thermal inertia (TI) of buildings are being worked out. The calculation for reaching maximal EE is based on average heat conductivity indicators of the building envelopes. In experimental calculations of conditions, the buildings are divided into 5–6 groups depending on the TI indicators.

In the EE optimisation, using TI great importance is ascribed to the climate investigations, particularly in the regions where there are prolonged periods with variable or unstable weather conditions. The basis of a method to achieve good results in the evaluation of the TI of buildings is the operation and maintenance of the heating system. The great number of days when the heating system can be interrupted and the TI of the buildings is used may produce a considerable EE effect and shorten the heating season (the use of the TI of a building may be considered as attraction of the RES, which is shown also by the maintenance estimate).

As indicated above, the TI of buildings may be increased if the heat resistance of the building envelope is taken into consideration, particularly in the new projects implemented using new building materials. Investigations use also modified models of the building designs

Most completely the sustainable EE has been achieved in the so-called "smart building" (SB) projects which may find wide application in the future. Therefore, it is important also to develop the methods of TI mentioned above just for the SB. SB is a house with a highly developed automatic system control for lighting and heating of premises, with local electricity generation and accumulation equipment, and so on. The computer system of the house can monitor various technical systems and communicate with the automatic control system considering the price of the supplied energy. Integration of the Smart Grid and SB into a joint system ensures optimal and economic guarantee of electricity, taking into account its usage. For further EE development, it is rational to integrate the SB and TI methods, which are still poorly investigated.

II. Improvement of Smart Buildings

"Smart buildings" (SB) with a highly developed automatic system control can monitor many technical systems every day and communicate with the automatic control systems considering the price of the supplied energy, including more complete use of the accumulated thermal energy in the envelopes of buildings, particularly when favourable meteorological conditions (warm days) set in. Highly developed electronic control systems cut off electricity supply using the renewable energy resources to a maximum extent, including the heat accumulated by day. With the development of the technical means of automatic control and increase in their applicability in the SB saturation of the SB with technical means, the quality and precision of operation of the control systems increase.

Along with the saturation of the SB with household appliances for lighting the rooms and increase of temperature insurance, the SB level increases, particularly if the wind generators of appropriate capacity and solar collectors and batteries for the use of solar energy are installed in the building. Of course, this involves the expansion and development of the SB control system. Besides, equipment for charging the automobile batteries during the night may be set up. As mentioned above, all this is connected with the SB supply system with electric energy and minimisation (optimisation) of the supplied energy. Therefore, the ratio of the renewable energy (RES) for the SB increases.

The use of the heat accumulated by the building envelopes by day during the night when there are corresponding weather conditions (particularly in the autumn and spring periods) is less investigated. As mentioned above, under the climatic conditions of Latvia such periods are rather lasting (under favourable conditions they may reach ½ of the heating season). In essence, it is just the use of the RES, and, at a sufficient indoor temperature, after the night sets in, a signal should be transmitted to the SB energy control system at the expense of the heat accumulated by day about the supply of all energy for heating the rooms with higher cutting of the prices. It should be additionally provided in the programme of the SB energy control system.

III. DEVELOPMENT OF THE THERMAL INERTIA INDICATORS OF BUILDINGS

The meteorological data for the weather conditions of Latvia (as a part of the Northern region of Europe) were used in the research.

The methodological studies of the development of architectural and building methods and materials allowed the formulation of such an indicator as the role of the thermal inertia of a building in the calculation methodology of the heat supply capacity. A scale has been developed for the determination of the heat supply capacity of buildings in order to achieve the necessary conditions for the comfort of the rooms under extreme conditions (at low outdoor temperatures) [1].

A motivation is given for the methods of raising energy efficiency in buildings having envelopes with low inertia, where the ratio of ventilation energy rises in the total consumption of energy.

In the early 1960-ties, the process of intense building started in Latvia, particularly in Riga. The traditional erection of brick houses was replaced by the fast industrial slab construction because the rates of the traditional construction could not satisfy the growing demand for the production, residential and public buildings. The industrial construction brought into practice the use of the lightweight concrete – aerocrete and claydite-concrete.

The better physical properties of aerocrete – the low unit mass of 600–800 kg/m^3 for aerocrete, as compared with 1100–1200 kg/m^3 for claydite-concrete, and the low heat conductivity of 0.26–0.37 W/(m^2·°C) for aerocrete, and respectively, 0.46–0.52 W/(m^2·°C) for claydite-concrete, in contrast to the effective (perforated) brick wall with its unit mass 1600 kg/m^3 and heat conductivity 0.64 W/(m^2·°C), determined the application of aerocrete in making the envelopes of buildings from industrial slabs.

This solution was seen as a promising perspective for the construction of cheap and, at the same time, sufficiently energy-efficient buildings. Technical normalisation of construction was adjusted to the social and economic requirements of that time, and it was very appropriate also for the existing building technologies.

For economic considerations, the envelope of the traditional brick houses was built as an effective brick wall, 510–540 mm thick, covered from both sides with a 2·15 mm thick sand and cement plaster [2].

The thermal resistance of such a brick envelope is R_o = 99 (m^2·°C)/W. The thermal resistance of aerocrete envelope slabs was normalised in the 1960-ties, meeting the demands of the building economy of that time, and was calculated as

$$R_o = n\left(t_{int} - t_{ext}\right) / \left(\Delta t^N \cdot \alpha_{int}\right) \text{(m}^2\text{·°C)/W}, \qquad (1)$$

where: n - a coefficient that characterises the condition of the envelope in relation to the external environment. For the envelope n = 1, but for the overhead coverings of upper storeys of the buildings and the buildings with attics n = 0.9.

t_{int} - the rated internal (indoor) temperature °C corresponding to the way the room is used (for dwelling houses t_{int} = +18 °C).

t_{ext} - the rated external temperature in winter in the geographical position of the building. It is used to determine the thermal resistance of the envelope and is selected depending on the thermal inertia (or massiveness) of the envelope D, which characterises the thermal endurance of the envelope and the entire house.

Δt^N - the normalised temperature difference between the indoor temperature and the temperature on the inner surface of the envelope, which is determined depending on the way the rooms are used. In the living rooms of the dwelling houses Δt^N = 6 °C.

α_{int} - the heat conductivity of the inner surface of the envelope equal to 8.7 W/ (m^2 ·°C) (~ const).

The thermal inertia of single-layer envelopes was calculated as

$$D = R \cdot S, \qquad (2)$$

but for multi-layer envelopes as

$$D = R_1 S_1 + R_2 S_2 + \ldots R_n S_n, \qquad (3)$$

where: R_1, R_2 … R_n are the thermal resistances (m^2·°C)/J of a multi-layer envelope or a building element, a single-layer envelope material or a multi-layer envelope material.

$S_1, S_2 \dots S_n$ are the heat intake coefficients J/ (m²·°C) of a single-layer envelope material or a multi-layer envelope material.
The heat intake coefficient was calculated as

$$S = 0.51\sqrt{\lambda \cdot C \cdot \gamma} \quad \text{(J/ (m}^2\cdot{}^\circ\text{C))}, \qquad (4)$$

where: λ - the heat conductivity of a layer of the envelope material, J/ (m²·°C).
C - the specific thermal capacity of a layer of the envelope material, J/ (kg·°C).
γ - the specific weight of a layer of the envelope material, kg/m³.

The rated thermal resistance of the envelopes of the dwelling houses under the climatic conditions of Latvia and, in particular, of Riga was calculated according to formula (1), the rated outdoor temperature being selected depending on the massiveness or thermal inertia of the envelope [3]:

R_o = 0.728 (m²·°C)/W - for massive envelopes with great thermal inertia, with the numerical value of thermal inertia $D > 7$.

R_o = 0.785 (m²·°C)/W - for the envelopes of medium massiveness, medium thermal inertia, with the numerical value of thermal inertia $4 < D \leq 7$.

R_o = 0.824 (m²·°C)/W - for the envelopes of small massiveness or small thermal inertia, with the numerical value of thermal inertia $D \leq 4$.

Using the already mentioned calculation values, external (outdoor) rated temperatures t_{ext}, which correspond to the thermal inertia of the envelope in compliance with the normative of that time for the calculation of R_o under the climatic conditions of Riga, were set:

- for massive envelopes of high thermal inertia with the numerical value of thermal inertia $D > 7$, t_{ext} = –20 °C, which corresponds to the mean temperature of the coldest 5 days;
- for the envelopes of medium massiveness, medium thermal inertia, with the numerical value of thermal inertia $4 < D \leq 7$, t_{ext} = –23 °C, which corresponds to the mean temperature of the coldest 3 days;
- for the envelopes of low massiveness and light weight, with the numerical value of thermal inertia $D \leq 4$, t_{ext} = –25 °C, which corresponds to the mean temperature of the coldest 1 day.

In the calculations of R_o, lower outdoor rated temperatures but greater temperature differences $t_{int} - t_{ext}$ correspond to the envelopes with a lower thermal inertia, and, hence, greater values of R_o. In the calculations of thermal inertia D, the increased value R of the layer of the envelope material and, hence, also the thickness of the envelope, is compensated by lowered heat intake S of the material with a low specific weight. The increased thermal resistances R_o of the envelope at lower values of thermal inertia should be ensured by the heat endurance of the buildings and normal thermal comfort in them when the outdoor temperatures in winter fall below –20°C, at which the losses of heat in the buildings, according to the demands of the standard, were calculated and a heating capacity to compensate them was defined [4].

In reality, the values D = 3.46 and D = 3.50 of thermal inertia of the lightweight concrete – claydite-concrete and aerocrete (industrial slabs of the envelopes) allow relating or qualifying them as envelopes of low massiveness, low weight and low thermal inertia ($D < 4$).

The full calculated thermal resistance of the envelopes made from lightweight concrete – claydite-concrete and aerocrete – industrial slabs – is correspondingly R = 0.664 (m²·°C)/W and R = 0.782 (m²·°C)/W. It should be stated that the real thermal resistance of the envelopes from lightweight slabs does not meet the demands of, and, by their actual thermal inertia, is even lower than the norm for the envelopes of high thermal inertia. As a result, the buildings with a low thermal inertia and a low rated thermal resistance R_o of the envelope have a low thermal endurance. The external temperature t_{ext} falling below the calculated normalised capacity of the heating systems, the temperature in the buildings starts falling rapidly below the lowest limit of comfort +18 °C causing further consequences to the indoor air – a possible still sharper decrease in the indoor temperature with great losses of heat through the moistened envelopes and still greater possibilities for the water vapour of the indoor air to condensate on the internal surface of the envelope, which increases thermal discomfort and decreases energy efficiency of the building [5].

In those times, the thermal inertia of buildings was formally identified with the thermal inertia of the envelope. Before the construction of buildings with the envelopes from lightweight concrete industrial slabs started, houses were basically built with massive brick envelopes and internal walls and with massive reinforced concrete inter-storey coverings. The building elements of the buildings possessed great heat accumulation capacity and, therefore, great heat endurance or thermal inertia.

The massiveness and heat endurance of the envelopes from large lightweight industrial slabs was lower and practically corresponded to the indicated rated thermal inertia $D < 4$. Therefore, in contrast to the brick houses, these buildings had lower energy efficiency with a worse thermal comfort in them.

Now these conclusions are confirmed in Latvia by the 40-year maintenance of the buildings from lightweight concrete slabs.

IV. EQUATIONS WITH THE OPERATIONAL DATA OF TI OF A SMART BUILDING ENVELOPE

A smart building SB is a perspective system for the development of energy efficiency with many highly developed technologies. The computer system of the house can daily monitor many technologies, as well as the local sources of energy and connections with the joint energy network (including the price of the supplied energy). The perspectives of SB development are based on the possibilities to increase the number of technologies of the house (describing the SB level of development), as well as the development of informatics. At the same time, the climatological research indicates favourable conditions for the use of the RES in Latvia, i.e. the energy accumulated in the envelope of the house by day can be used during the night, without resorting to other sources of energy (including the local sources of energy and the energy of the wind, the sun, and the like) because they are more expensive than the heat accumulated by the SB envelope under favourable meteorological conditions.

From the economic point of view, the percentage of energy saving achieved by an EE measure in the total energy consumption before starting the EE measure (renovation of the building, etc.):

- The cost of energy saving achieved by the EE measure;
- Energy saving gained from the renewable energy resources (RES) (%) and (MWh);
- The cost of an MWh of the saved energy.

The best selected measures will be the ones which have achieved the highest percentage of energy saving of the energy consumption before starting the EE measures at the lowest cost of 1 MWh. An important factor for the selection of measures is certification of buildings, because only completely finished and certified buildings can be used for sustainable energy planning (development of an action plan) considering that the data of a certificate or a provisional certificate are correct and reliable. Certification of buildings is a separate problem not within the scope of the present investigation [6].

The data of a provisional certificate are applied in order to work out an action plan before starting the project of the measure. The long-term EE action plan (till the year 2020) provides for the intended measures but the short-term action plan (2 – 3 years) includes only the measures which have been elaborated for the economically sound projects considering both the investments and the maintenance costs. Besides, the choice of the available primary resources (the fuel) will be of great importance. The use of the RES in the selection of the EE measures is conditioned by the same criteria as in the selection of measures with respect to using fossil energy. The saved energy is estimated including the RES, but an additional criterion is connected with the minimisation of the CO2 emissions. If the EU Directive sets an additional task for the country to increase the use of the RES, the level of the RES to be achieved becomes a selection criterion [7].

TABLE 1
THE NUMBER OF DAYS WITH UNSTABLE WEATHER CONDITIONS (IN LATVIA)

Outdoor air t_{OA}°C	±0 ÷ +10	±0 ÷ -5	-6 ÷ -10	-11 ÷ -15	-16 ÷ -20	-21 ÷ -25	-26 ÷ -30
Duration of stability in days	92	81	24	12	6	5	3

The RES play an important role in the analysis of the thermal inertia of buildings; they increase the percentage of the saved energy in a period of unstable weather conditions. Under corresponding weather conditions when the thermal inertia of the building is sufficient and the heat accumulated during the day can ensure the heat consumption at night, it is possible to shorten the heating season and increase the percentage of the saved energy [8].

Duration of the heating season is the sum of days when the outdoor air temperature meets the conditions of the beginning and the end of the heating period and the days when the outdoor air temperatures are lower than the temperatures fixed for the start and the finish of the heating season. According to the observations of the Latvian Meteorological Service, the duration of steady or stable outdoor air temperatures is statistically determined for the forecasted heating period at their various values.

Taking into account the unpredictable outdoor air temperature oscillations in the autumn and spring periods, i.e. the beginning and the end of the heating periods, and the great thermal inertia of the inspected massive buildings, the start of the heating period is set with a three days' shift in relation to the defined start, assuming a probability from experience that already three days later the outdoor air temperature will rise, and the beginning of the heating period will eventually be postponed until the defined outdoor air temperature for the start of the heating season sets in [9].

The data in Table 1 illustrate that in Northern Europe where there is great consumption of thermal energy, there are also periods with unstable weather conditions when the thermal inertia of buildings can be used to ensure heat supply without consuming energy (in essence, this is application of the RES when the surrounding heat is accumulated during the day (see Table 1; from -5 to +10 °C). Close to the sea, the number of such days may be even larger by 10%.

Utilisation of the RES in the EE measures in order to raise the percentage of the saved energy can be also achieved by increasing the thermal inertia of the building and the thermal resistance (RS) of its envelope (see Formula 2)[10].

This needs economic substantiation (RES optimization), gaining additional days when it is possible to get along with the heat accumulated during the day from the environment, thus increasing the amount of the saved energy and reducing its cost.

V. Conclusions

In-depth analysis of the thermal inertia of buildings showed that it can be applied in an extraordinary way regarding the energy efficiency (EE) measures in order to increase the amount of the saved energy and to reduce its cost by attracting the RES from the surrounding area.

It costs almost nothing in the buildings with great thermal TI, but the TI of the houses erected from modern building materials may be increased due to economical optimization of extensive use of the RES of the surrounding area.

The value of the EE measure is the higher, the more energy is saved and the cost of the saved energy is lower considering the costs for the implementation of an EE measure. This can be achieved by better use of the TI of buildings and decrease of the consumption of energy for the operation of the heating system.

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