*Наведено отримані шляхом натурних досліджень дані по розподіленню температури повітря в приміщенні за використання електротеплоакумулюючого обігрівача для опалювальних сезонів 2014–2015 та 2015–2016 років. Встановлено значення коливання температури по висоті приміщення та виявлено зв'язок між вказаними коливаннями та певними режимами роботи приладу*

*Ключові слова: акумуляційне електроопалення, теплоакумулююча електропіч, теплонакопичувач, електротеплоакумулюючий обігрівач, температурний режим приміщення*

*Приведены полученные путем натурных исследований данные по распределению температуры воздуха в помещении при использовании теплонакопителя для отопительных сезонов 2014–2015 и 2015–2016 годов. Установлены значения колебания температуры по высоте помещения и определена связь между указанными колебаниями и определёнными режимами работы прибора*

*Ключевые слова: аккумуляционное электроотопление, теплоаккумулирующая электропечь, теплонакопитель, электротеплоакумулирующий обогреватель, температурный режим помещения*

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# ANALYSIS OF THE TEMPERATURE DISTRIBUTION IN A SPACE HEATED BY A DYNAMIC (FAN) STORAGE HEATER

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## 1. Introduction

Today in Ukraine and worldwide there is an urgent task for the rational use of surplus electricity. One effective means of disposal of such surpluses is electric storage heating system. This mean is stimulated with a sizeable reduction in the cost of electricity during the hours with excess generation of electricity.

There are various options for implementing such systems. One is storage heaters [1]. Storage heater is a separate device that stores heat in a solid-state material. Heat is generated with resistance heaters which use electricity during the period of low electricity cost. The stored heat is used by the device for heating the room beyond the periods of low electricity costs.

Shown appliances are used for heating both residential and office spaces [2–4], and small commercial premises [5]. For the latter, it is not always possible to use water central heating system, and so the use of room electric storage heating is a relevant decision.

There are several types of storage heater design, which, in particular, differ in a range of regulated heat output. The widest regulated heat output is provided with a design of a storage heater known as “dynamic” [6]. Heat output from a dynamic storage heater is divided into: non-regulated – through an outer surface and regulated – through internal air channels in the design of the device. The regulation of heat output is carried through changing the amount of air passing through the internal channels with a fan. When a fan is off, a storage heater mode is defined as static. When a fan is on, it is defined as dynamic.

Storage heaters of dynamic design are recommended for use in Ukrainian climate [7].

## 2. Literature review and problem statement

The determination of the required value of device “charging” (the amount of stored heat) is often based only on the ambient temperature, as shown in [8]. Wherein the room temperature, when a storage heater is used, is considered to a priori meet the design data. However, such simplification may lead to errors in determining the need for heat because users establish room temperature in their sole discretion, which can be significantly different from the design.

The state-of-art studies of how users choose room temperature are analyzed below.

In [9], the comparison of room temperature with the values that were used for the heating design of these rooms is performed. This comparison showed that the real value of room temperature in average was less than taken for heating design.

Similar studies are presented in [10]. The dependence of the room temperature set on the type of a consumer (his home, age, preferences, etc.) was studied. It should be noted that the research has shown some unexpected results. It concerned those consumers who during the survey indicated that they wanted to reduce the cost of heat. According to [10], these consumers set a higher temperature than those who neither agreed nor denied the need for reducing the cost of heat. But the averaged room temperature in this study also was lower than in the project.

Unlike the previous two, the study from [11] revealed a situation when customers set the room temperature significantly higher than it was designed. As a result, when the 2014 winter was 28 % warmer than it was expected by the design project, heating costs were 23 % higher than it was evaluated in the design.

It can be preliminarily concluded that the study of room thermal conditions requires advanced study for temperatures different from those used for a design. This is especially true for the rational design of a storage heater "charging" as the required amount of stored heat depends greatly on how room temperature changes through a day.

However, there are some questions about the reliability of such studies. In [9–11], room temperature was considered as a single value without fluctuations at different points in the room. The temperature values in these studies were derived from the indicators of thermostats.

Now let's consider how the distribution of room temperature and its changes were studied during the research of heat output from a storage heater.

In [12], the temperature record of dwellings, heated with storage heaters, made only through one temperature sensor in the room is shown. Six users took part in the research. As a result, the temperature records of two of these six users were substantially lower than estimated. Lower temperature was explained as follows. Thermostats were located in the hallway. And those two users closed the doors, which lead to the hallways, thus limiting the movement of heated air from heated rooms to the hallway. So, the data did not represent the temperature conditions of the premises, which were mainly occupied by residents.

In [13], the study of a storage heater was considered only for the case when a storage heater is turned on and off. The duration of this study was 100 hours. The temperature in the room was constantly changing. At baseline (0 h), it was 20 °C. In the period from 0 hours to about 56 hours, the temperature gradually decreased to 14 °C. After that, the room temperature increased, reaching 21 °C at the end of the study (100 hours). The paper does not specify exactly how the temperature values were obtained. Also, a change in the room temperature depending on the storage heater fan was not considered.

In [14], the data of the observations on thermal conditions of the premises, heated by a dynamic storage heater were presented. The property was located in the Shetland Islands (UK). The study lasted from March to October 2012. Although this period is generally considered warm season, the authors of [14] made a remark that the conditions typical for cold season also took place during this period.

In [14], 18 rooms were studied, the number of data channels for each ranged from 12 to 14. The frequency of recording ranged from 1 to 5 minutes. During these studies, heat output from a storage heater predominately was unregulated. That means that a fan of a storage heater wasn't predominately used. If there was a need to use a fan, then the authors [14] remarked that a fan could be switched on and off at intervals of 1 min. However, in a computer simulation, which was compared with full-scale study, the authors [14] used a longer interval, which amounted to 5 minutes. This reduction was based on the similarity of results when using both intervals.

The authors [14] didn't indicate to what extent room temperature varied at different points of a room, and they didn't study a fan mode as a separate issue.

From the literature review, the following conclusions can be made:

1. The use of storage heater is mostly studied for dwellings. The application of storage heaters for non-residential premises is much less studied.

2. Current research of storage heater modes does not pay enough attention to the temperature distribution in the room. Accordingly, there are no data to determine the best modes for fans of dynamic storage heaters.

3. The studies do not contain the information on errors of temperature measurement and the accuracy of the data. That makes it impossible to compare the results of these studies and use them beyond a particular experiment.

Therefore, there is a need to conduct more detailed investigations of storage heaters. This would assist to create a more informative thermal model of a room heated by a storage heater. Also, this kind of information would assist in a more precise evaluation of the stored heat amount which depends on the set room temperature and thus there would be a positive impact on the ability of the storage heater automatics to predict the required level of "charge".

## 3. The purpose and objectives of the study

The aim is to identify the characteristics of the functioning of a storage heater in dynamic and static modes by mathematical processing of data obtained during the experiments with the temperature parameters in a separate room within a few heating seasons.

To achieve this goal, the following tasks were set:

– to develop a scheme of the experiment;

– to identify the error of the experiment;

– to record the room temperature at certain points of the space within the heating season;

– to analyze the data and use the data to detect specific changes in temperature depending on the mode of the device.

## 4. Description of the experiment to determine the temperature distribution in the room

### 4. 1. Description of the place of the experiment in order to determine the temperature distribution in the room

Field research was carried out at the premises of the pumping station of JSC "Kyivkhlib", Production department No. 1 (Ukraine, Kyiv, Bohatyrska St., 5). Previously this space has been heated by conventional electric space heaters (convectors) and, by replacing these devices with storage heaters, the operational costs of heating has been reduced.

### 4. 2. Description of the experiment to determine the temperature distribution in the room

A functional diagram of the space heating and automation panels are shown in Fig. 1. The marking to designate the automation equipment was made in accordance with GOST 21.404-85 "Designations of conditional devices and means of automation in circuits".

The following description of the storage heater automation system refers to the heating season 2014–2015. It is for this heating period the values of the temperature sensors TE2 and TE4 indicated below are selected. For the next heating seasons, the temperature values for these sensors were lowered by 1 °C.

The work of the automation system starts with determining the value with a temperature sensor TE2. If the temperature is less than 15 °C, then the controller-logger TIC9 gives the command to turn on the contactor NS5 and, therefore, start the storage heater fan. The storage heater fan sucks air from the room and blows it through the channels fitted in the heat storage materials, where the air is heated. Heated air is supplied to the served room. Heating process continues until the temperature sensor TE4 records air temperature over 16 °C. In this case, the controller-logger TIC9 gives the command to disable the contactor NS5 and, therefore, stop a fan storage heater. The system stops before the temperature measured by the sensor TE2 is below 15 °C, and then a new cycle of heating the room begins.

To collect experimental data, the system involves a meter-logger TIR8, which records the measurement results of the temperature sensor TE3 to obtain data that would increase the validity of the mathematical data processing of sensors TE1 and TE2. With the help of the PI485/USB system, this meter-logger also is able to back up information from the "logger" type device on the PC.

Heating of the heat storage material ("charge") of a storage heater takes place when a command is generated by a real-time timer KS7. The command from the timer KS7 is fed to the contactor NS6, which connects the storage heater to the circuit 380/220 V, 50 Hz. The timeframe of the command is set to match the time of the cost-efficient "night" tariff (7 hours) and a minimum consumption of the enterprise afternoon (3 hours).

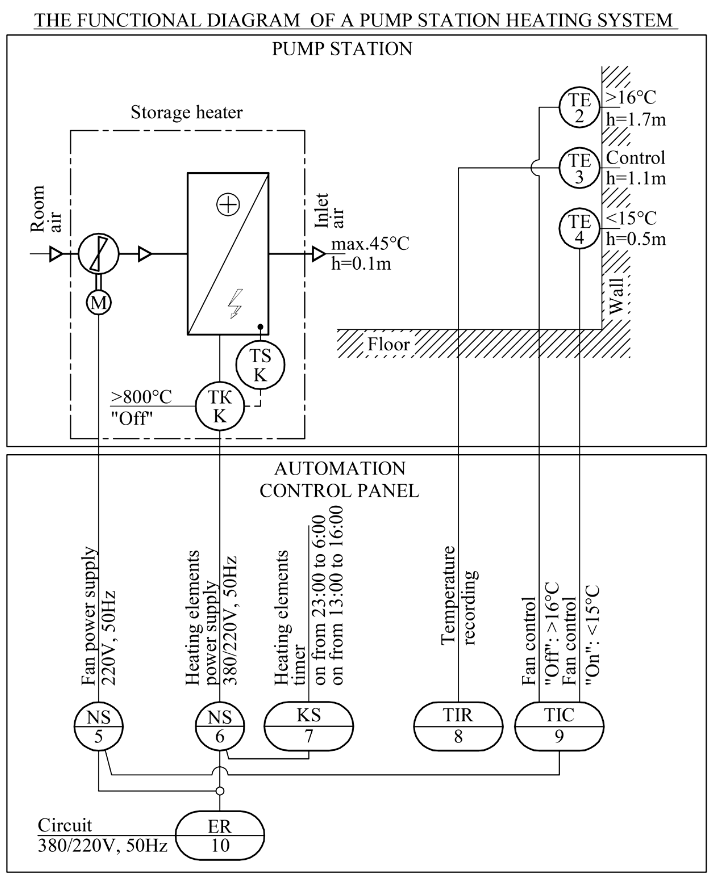


Fig. 1. The functional diagram of the space heating and automatic control panel: 1 — storage heater, a modified design based on the model ADL-3018, 380/220V, 50 Hz, 3 kW, made by ELNUR, Spain); 2—4 — temperature sensors TSP-303p (Pt100), range — 40 °C...85 °C, made by SPC "RegMik", Ukraine; 5 — single-phase contactor, ESB20 type, $I_n$=20 A, made by ABB, Germany; 6 — three-phase contactor, DILM40 type, $I_n$=40 A, made by EATON, USA; 7 — real-time timer, UT1 type, made by OWEN, Russia; 8 — dual-channel meter-logger, I2I type, made by NPF "RegMik", Ukraine; 9 — dual-channel controller-logger, RP2I type, made by NPF "RegMik", Ukraine; 10 — NIK2301 — three-phase electricity meter, NIK2301 AP1 type, direct connection, 5A (100 A), accuracy class 1.0, made by "NEC", Ukraine

As temperature sensors, TSP-303p (Pt100), made by NPF "RegMik", Ukraine was used. As a meter-logger, RP2l, made by NPF "RegMik" Ukraine was used.

Location of temperature sensors is shown in Fig. 2.

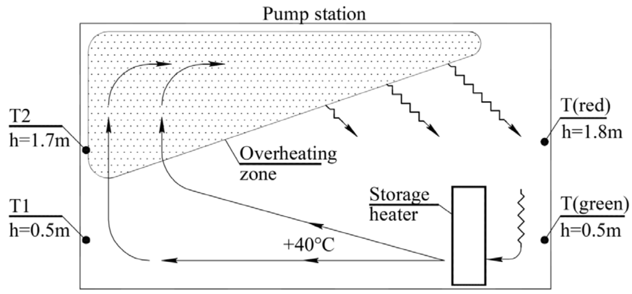


Fig. 2. Overheating zone of pump station indoor air during air outlet (fan is on)

Sensors T1 and T2 in Fig. 2 correspond to the sensors on the automation diagram (Fig. 1) labeled TE2 and TE4, respectively. To ensure the reliability of the data received from the sensors T1 and T2, a measurement control system was introduced. This system consists of standalone temperature loggers LOGGER100 TV (made by OWEN, Russia). The loggers were placed near the sensors T1 and T2 and they are not shown in Fig. 2. Further, the loggers LOGGER100 TV are denoted as T(1) and T(2), which respectively control parameters T1 and T2. To measure the temperature on the opposite side of the room, standalone temperature loggers LOGGER100 TV indicated in Fig. 2 as T(red) and T(green) were installed.

### 4. 3. Identification of the error of measurement to determine the temperature distribution in the room

When processing information to evaluate the data quality, the data caused by outside influence on the operation mode of a storage heater, envisaged in the research has been identified and discarded. It concerns the data obtained in the period of power failure, violation of the thermal regime of space during periods of routine maintenance by repair crews or visiting a room by staff on duty and so on. Also, the data were preliminary analyzed for suitability (completeness) for further calculations to determine the required parameters and used if this requirement was consistent. The purpose of this approach was to reduce the number of factors that could adversely affect the quality of comparison of the data obtained during the study with those of the analysis of the theoretical model of a storage heater.

Calculation of temperature measurement errors is aimed at studying the characteristics of a storage heater rather than arrangement of a stable thermal regime in a room. That is why this paper does not consider the proof of the thermal regime stability by the corresponding metrological calculations. For this reason, any standardized calculations and confirmation of metrological characteristics as for measuring channels for industrial or scientific equipment are not used. Further calculation is made for reasons of clarifying information about the accuracy of the data.

The data error is analyzed based on the fact that the overall measurements of room temperature are within 10...25 °C. Accordingly, it is necessary to determine the error for the lower limit which is 10 °C and the upper limit which is 25 °C. As a result, the accuracy of the database located within these limits will be obtained.

**4. 4. Calculation of the temperature measurement error made by devices used to determine the temperature distribution**

The characteristics of the temperature sensor (resistance temperature detector) TSP-303p (Pt100), NPF "RegMik", Ukraine are presented in Table 1.

Table 1

Characteristics of TSP-303p

| Characteristic name | Characteristic value |
|---|---|
| Measurement range, °C | −40...+85 |
| Tolerance class | A |
| Measurement response time, $\tau_r$, s | 6...8 |

For A tolerance class (GOST 6651-2009), an absolute temperature measurement error $X_{tt(25\,°C)}$=25 °C is:

$$\Delta_{tt(25\,°C)} = \pm\left(0.15+0.002\cdot|t|\right) = \\ = \pm\left(0.15+0.002\cdot|25|\right) = \pm 0.2\ °C \quad (1)$$

and relative error:

$$\gamma_{tt(25\,°C)} = \left(\Delta_{tt(25\,°C)}/X_{tt(25\,°C)}\right)\cdot 100\,\% = \\ = \left(0.2/25\right)\cdot 100\,\% = 0.8\,\%. \quad (2)$$

For A tolerance class (GOST 6651-2009), an absolute temperature measurement error $X_{tt(10\,°C)}$=10 °C is:

$$\Delta_{tt(10\,°C)} = \pm\left(0.15+0.002\cdot|t|\right) = \\ = \pm\left(0.15+0.002\cdot|10|\right) = \pm 0.17\ °C \quad (3)$$

and relative error:

$$\gamma_{tt(10\,°C)} = \left(\Delta_{tt(10\,°C)}/X_{tt(10\,°C)}\right)\cdot 100\,\% = \\ = \left(0.17/10\right)\cdot 100\,\% = 1.7\,\%. \quad (4)$$

When connecting the sensor TSP-303p (Pt100), a code is put into the program of the dual-channel controller-logger of RP2l type (NPF "RegMik") that corresponds to the type of a sensor. As a result, the upper limit of measurement RP2l automatically adjusts to the value $X_{uc}$=85 °C, and the lower limit – to $X_{lc}$=–45 °C. Also, based on the device certificate, the limit of permissible basic reduced error is $\gamma_c$=0.5 %. The absolute error of the device throughout the measurement range is (GOST 8.401-80):

$$\Delta_{tc} = \left(X_{uc}-X_{lc}\right)\cdot\gamma_c/100\,\% = \\ = \left(85-(-45)\right)\cdot 0.5/100\,\% = 0.65\ °C. \quad (5)$$

As a rule, the calculation of the data error, in addition to direct assessment of equipment errors, involves an analysis of other factors that could affect the accuracy of measurements. For example, such factors include interference from voltage fluctuations or temperature drift of devices. The following factors were analyzed:

– sampling error, the calculation of which must be done for any device, which provides recording of a signal assigned with a discrete-time signal;

– the response time error of the temperature sensor, the calculation of which is connected with the need of taking into account the real speed of the process which is measured;

– the error because of interference in the conductors that connect the temperature sensor to the measuring device;

– the error because of voltage fluctuations.

The relative temperature measurement error for $X_{tc(25\,°C)}$==25 °C is:

$$\gamma_{tc(25\,°C)} = \left(\Delta_{tc(25\,°C)}/X_{tc(25\,°C)}\right)\cdot 100\,\% = \\ = \left(0.65/25\right)\cdot 100\,\% = 2.6\,\% \quad (6)$$

and the relative temperature measurement error for $X_{tc\,(10\,°C)}$==10 °C is:

$$\gamma_{tc(10\,°C)} = \left(\Delta_{tc(10\,°C)}/X_{tc(10\,°C)}\right)\cdot 100\,\% = \\ = \left(0.65/10\right)\cdot 100\,\% = 6.5\,\%. \quad (7)$$

Thus, it can be concluded that the lower the temperature, the greater the data error.

**4. 5. The data recovery error, resulting in the determination of temperature distribution**

For RP2l, Table 2 shows the parameter "storage period", $\tau_d$, with which the sampling rate can be estimated.

Table 2

Characteristics of RP2l

| Characteristic name | Characteristic value |
|---|---|
| Nominal voltage, V | 220 |
| Voltage tolerance, % | 10 |
| Measurement period, s | 1 |
| Data storage period, $\tau_d$, min | 1–9999 |
| Limit of permissible basic reduced error of temperature measurement (without the sensor error), $\gamma_k$, % | 0.5 |
| Non-volatile memory cell number | 10920 |

Different values of $\tau_d$ were used in the study for data collection. When there was a need for the most detailed, considering the technical capabilities of the device, information about the process, $\tau_d$=1 min was taken. For general information about the course of the process, such as frequency of turning on the fan or the average temperature in the room, $\tau_d$=5...10 min was used.

Data recording in different modes was forced. It was due to the fact that the memory capacity of the device at RP2l $\tau_d$=1 min was enough to record the information for only incomplete seven days. In case of exceeding this limit, the recording was continued in a cyclic mode with the original memory cells, deleting the previous data.

For estimation of the data recovery error with the selected $\tau_d$=1 min, it is necessary to identify the maximum rate of temperature change in the room when it is heated by a storage heater when a fan is on (duration of the period when a fan is on). It can be traced on the temperature curves in the following circumstances: the highest outside air temperature, at which a storage heater begins to use a fan to maintain the thermal regime of the space.

As follows from the analysis of the curves developed during the study, such condition was the launch of the storage heater fan (Fig. 3) on 04.11.2016. Before the fan was on, a storage heater was fully "charged" without launching a fan (there has been only heat loss through the outer surface of the device, which compensated for the space heat loss). The outside temperature at the time of start-up was 1.1 °C, and for the first in a month fell below zero to –1.5 °C. The period of heating the air in the room made $\tau_p$=7.5 min. The rate of change in the room temperature is lower (i. e., a fan works longer) under certain circumstances. Such circumstances may be, for example, incomplete "charge" of a storage heater or the outside air temperature, which is less than the above-mentioned temperature at the first launch.

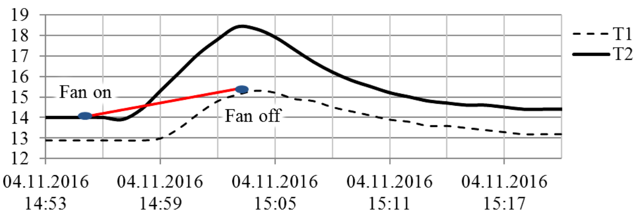


Fig. 3. Room temperature change between two launches of a fan, °C: T1 — temperature measured by the sensor TE4; T2 — temperature measured by the sensor TE2

According to [15], the relative data recovery error for a given period is determined by the formula:

$$\gamma_{ds(i)/(j)} = \frac{1}{2}\cdot\left(\frac{\pi\cdot\tau_{(i)}}{\tau_{(j)}}\right)^2. \tag{8}$$

According to the formula (8), for $\tau_p$=7.5 min and $\tau_d$=1 min – $\gamma_{ds1/7.5}$=8.8 %, for $\tau_d$=5 min – $\gamma_{ds5/7.5}$=220 %, for $\tau_d$=10 min – $\gamma_{ds10/7.5}$=880 %.

Thus, for the study of the room air heating curves, only the data are fit which were obtained with $\tau_d$=1 min. This does not mean that the data obtained with $\tau_d$=5...10 min have no practical use. With a further decrease in the outside temperature, duration of the room temperature change could make a few hours. The duration of one of such periods is $\tau_p$= 480 min, and the relative data recovery error with $\tau_d$=10 min is:

$$\gamma_{ds10/480} = \frac{1}{2}\cdot\left(\frac{\pi\cdot\tau_d}{\tau_p}\right)^2 =$$

$$= \frac{1}{2}\cdot\left(\frac{10\pi}{480}\right)^2 = 0.0021 = 0.21\ \%. \tag{9}$$

It means that $\tau_d$=10 min at $\tau_p$=480 min ensures the accuracy of recovery required to use certain data groups in subsequent calculations.

The data recovery error is not directly related to the measurement error, but must be considered in the mathematical processing of certain groups of the data obtained. This is due to the fact that the value of the data recovery error, if the wrong approach is used, may be unacceptable for calculations.

**4. 6. Sampling error**

According to the "measurement period" $\tau_{mp}$=1 s, indicated in the certificate of the device RP2l, the sampling error, calculated with the formula (8), is $\tau_p$=7.5 min, $\gamma_{mp/7.5}$=0.0024 % for the smallest period of the fan launch.

**4. 7. Response time error of the temperature sensor**

According to [15], the response time error of the temperature sensor can be taken into account, as well as the sampling error, where $\tau_r$ of a sensor is correlated with the parameter "data storage period" $\tau_d$. The duration the shortest period of the fan launch is $\tau_p$=7.5 min, and the relative response time error at $\tau_r$=8 s (0.133 min) is:

$$\gamma_{si} = \frac{1}{2}\cdot\left(\frac{\pi\cdot\tau_d}{\tau_p}\right)^2 = \frac{1}{2}\cdot\left(\frac{0{,}133\cdot\pi}{7{,}5}\right)^2 = 0.0016 = 0.16\ \%. \tag{10}$$

Compared to the temperature measurement and data recovery errors, this error is insignificant.

**4. 8. Error because of interference in the conductors that connect the temperature sensor to the measuring device**

This error is introduced in the calculation to improve its reliability. This error occurs because the conductors are not shielded, so they are susceptible to certain types of interference. Moreover, interference is inevitable in the industrial zone, which the studies were carried out.

According to the recommendations [15], the relative error such as $\gamma_{pp}$=0.1 %, which corresponds to 1 mV of a harmful signal per 100 mV of a useful signal at the input meter resistance of 1 MW can be taken.

**4. 9. Errors because of voltage fluctuations**

In the certificate of RP2l, it is stated that the voltage tolerance is 10 %. This gives the grounds to suggest that the instrument uses the common scheme with a stabilization coefficient K=25. That is, the voltage tolerance of 220 V±10 % can be up to (10/25=0.4) 0.4 %. This value is the relative error of voltage fluctuations $\gamma_v$=0.4 %, which should be taken into account when calculating the measurement accuracy.

**4. 10. Calculation of the room temperature measurement error**

All calculated relative errors are shown in Table 3. This table also specifies the distribution laws and the corresponding coefficients to calculate the standard deviation for each of these errors [15].

Table 3

Experimental study errors

| Error source | Symbol | Value of γ at t=10 °C | Value of γ at t=25 °C | Distribution law | Coefficient of standard deviation ($k_s$) |
|---|---|---|---|---|---|
| Temperature sensor | $\gamma_{ts}$ | 1.7 | 0.8 | Normal | 1.64 |
| Controller | $\gamma_{tc}$ | 6.5 | 2.6 | Uniform | 1.73 |
| Signal sampling at $\tau_d$=1 s and $\tau_p$=7.5 min | $\gamma_{mp/7.5}$ | 0.0024 | 0.0024 | Uniform | 1.73 |
| Temperature sensor response time | $\gamma_{sr}$ | 0.16 | 0.16 | Normal | 1.64 |
| Interference in the conductors | $\gamma_{ic}$ | 0.1 | 0.1 | Arcsine | 1.41 |
| Voltage fluctuations | $\gamma_v$ | 0.4 | 0.4 | Triangular | 2.54 |

All relative error values listed in the table are assigned to uncorrelated (unrelated by a common cause). Calculation of the sum of such errors is not performed by simple arithmetic addition, but after clarifying the error distribution law and the corresponding standard deviation factor is defined as the geometric sum of standard deviation, $\sigma_\Sigma$:

$$\sigma_\Sigma = \sqrt{\sum_{i=1}^{N} \sigma_i^2}, \quad (1)$$

where $\sigma_i$ – standard derivation of the i-th error ($\sigma_i=\gamma_i/k_{si}$).

Data from the calculation of standard derivation are shown in Table 4. At a temperature of 10 °C, $\sigma_\Sigma$=3.903, and at 25 °C, $\sigma_\Sigma$=1.593.

Table 4

Data for determining the error of experimental studies

| Error source | Symbol | Value of σ at t=10 °C | Value of σ at t=25 °C |
|---|---|---|---|
| Temperature sensor | $\sigma_{ts}$ | 1.037 | 0.488 |
| Controller | $\sigma_{tc}$ | 3.757 | 1.503 |
| Signal sampling at $\tau_d$=1 s and $\tau_p$=7.5 min | $\sigma_{mp/7.5}$ | 0.0014 | 0.0014 |
| Temperature sensor response time | $\sigma_{sr}$ | 0.1 | 0.1 |
| Interference in the conductors | $\sigma_{ic}$ | 0.071 | 0.071 |
| Voltage fluctuations | $\sigma_v$ | 0.157 | 0.157 |

To restore the relative error, it is assumed that the biggest impact on the form of the distribution law of errors is made by errors with uniform distribution law. The distortion of the distribution law of the sum of errors because of the contribution of errors with other distribution laws is neglected. Thus, to restore the relative error, the standard deviation for the uniform distribution law $k_s$=1.73 is used.

At $\tau_d$=1 min, $\tau_p$=7.5 min and temperature of 10 °C:

$$\gamma_{\Sigma(10)} = \sigma_\Sigma \cdot k_s = 3.903 \cdot 1.73 = 6.7\ \%. \quad (2)$$

At $\tau_d$=1 min, $\tau_p$=7.5 min and temperature of 25 °C:

$$\gamma_{\Sigma(25)} = \sigma_\Sigma \cdot k_s = 1.593 \cdot 1.73 = 2.8\ \%. \quad (3)$$

The values of the relative errors obtained from the formulas (12), (13) indicate the sufficient for the purposes of the study accuracy of the temperature measurement, even when recording the fastest process of the room air heating.

It should be added that about 500.000 temperature values (in total, from seven separate sensors) were recorded within two heating seasons for the storage heater operation study. Of these, after the data processing was made, the base of 75.000 time-synchronized measurements was developed. This has provided enough information for the study of the room air heating processes and analysis of the storage heater features. This fact indicates that the accuracy of the measurements is certainly important for the study, but the task of collecting data on the storage heater operation in practical conditions was paramount.

**4. 11. Errors of temperature measurement controllers**

In the specifications of the device LOGGER100 TV, the measurement range of –40...+70 °C, which satisfies the requirements for the temperature range taken in the study, and the absolute error of ±1 °C (in the range of –10...+40 °C) are specified. A graphical comparison of the data obtained by LOGGER100 TV with those from temperature measurement sensors T1 and T2 is shown in Fig. 4.

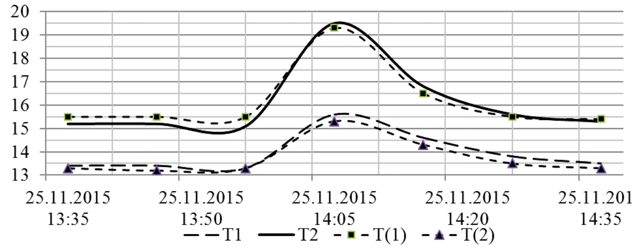


Fig. 4. Temperature curve depending on the sensor readings: T1, T2, T1 is followed by T(1), T2 — T(2) °C

Since the absolute error of the RP2l is ±0.65 °C and less than the absolute error of LOGGER100 TV, RP2l was considered as a "basic" device and LOGGER100 TV – as a "control" device.

## 5. Discussion of results of field studies that appear when calculating the temperature distribution

The curves of temperature change (Fig. 5) at different points in space show a significant difference between the value of temperature sensors T1 and T2 and T(green) and T(red). This fact points to the formation of the air overheating zone, which refers to adverse events in heating systems, and thus requires special consideration.

As follows from Fig. 2, the sensor T2 is placed in a potential air overheating zone. Here, the overheating means the increasing temperature gradient difference along the height of the space. Therefore, further analysis is conducted to determine the average temperature gradient and the share that falls within the air overheating periods in relation to the entire period of the heating season.

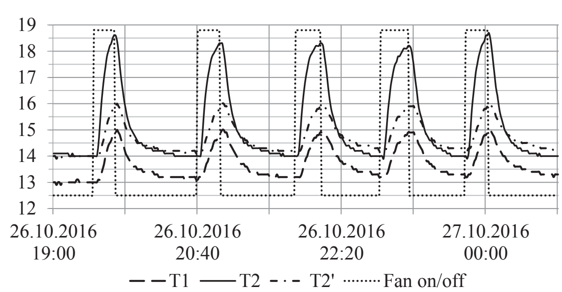


Fig. 5. Room temperature curves depending on the fan mode (on or off), °C

Let's think that if there was no overheating, then the temperature curves T1 and T2 would have the same change pattern as the temperature curves T(green) and T(red), that is the time-constant value of the difference between T(green) and T(red). For this purpose, it is necessary to draw an auxiliary line (Fig. 6) of the temperature curve T2', which would be different from T1 by some constant value (T2' is shown schematically in Fig. 6).

To determine this value, it is necessary to calculate a statistically significant difference between T1 and T2, when a storage heater fan is off, and the process of cooling the air in the room becomes sustainable. As the above example of overheating refers to the heating period 2016–2017, the base of which is incomplete, data were obtained from the database of the heating period 2014–2015 regarding the number of periods (N) in which the temperature T1 deviated by no more than ±0.2 °C for 30 min (Table 5).

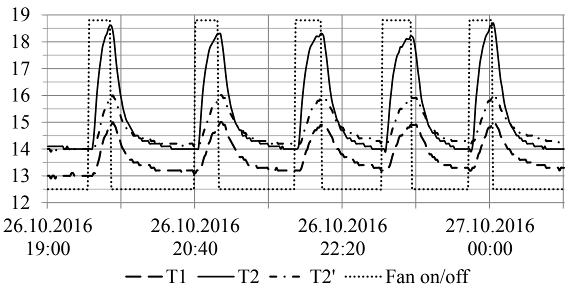


Fig. 6. Room temperature curve depending on the fan mode (on or off) with a constant gradient, °C

Table 5

The probability of temperature T1 during the 2014–2015 heating season

| T1, °C | N | $P_i$ |
|---|---|---|
| 13.5 | 5 | 0.019 |
| 13.4 | 7 | 0.027 |
| 13.3 | 20 | 0.077 |
| 13.2 | 48 | 0.185 |
| 13.1 | 48 | 0.185 |
| 13 | 40 | 0.154 |
| 12.9 | 24 | 0.093 |
| 12.8 | 30 | 0.116 |
| 12.7 | 26 | 0.1 |
| 12.6 | 8 | 0.031 |
| 12.5 | 3 | 0.012 |

As follows from Table 5, the periods of sustained temperature T1 with the highest probability $P_i$ ($P_i=N_i/\Sigma N_i$) fall within the range of 12.7...13.3 °C. Therefore, the first two and last lines will be rejected in further calculations, and for other values, the average value of the difference T2–T1 for a given T1 (Table 6) and the most probable value of the difference are determined.

To create the conventional temperature T2', we assume that its value reaches $T2'=T1+\Sigma(\Delta T{\cdot}P_i)$, where $\Sigma(\Delta T{\cdot}P_i)=$ $=2$ °C, and make adjustments to the database, based on which we get the temperature difference T2–T2' and the number of periods of overheating $N_t$ (Table 7).

Mean overheating temperature is $T_{ov}=1.8$ °C. The number of heating cycles with overheating is $N_t=1952$, the number of cycles without overheating is $N_t=14$. The total share of the length of overheating periods in the heating season 2014–2015 is 0.0725 (7.25 %).

The above method is used to calculate the mean overheating in the heating season 2015–2016.

First, the number of periods N in which the temperature T1 does not deviate by more than ±0.2 °C for 30 minutes is determined. As follows from Table 8, the periods of sustained temperatures T1, PI with the highest probability fall within the range of 13.1...13.8 °C.

Table 6

The probability of mean temperature ΔT=T2–T1 in a static mode during the 2014–2015 heating season

| T1 | ΔT=T2–T1 | N | $P_i$ | $\Delta T{\cdot}P_i$ |
|---|---|---|---|---|
| 13.3 | 2.03 | 20 | 0.085 | 0.173 |
| 13.2 | 2.01 | 48 | 0.203 | 0.408 |
| 13.1 | 1.93 | 48 | 0.203 | 0.392 |
| 13 | 2.17 | 40 | 0.169 | 0.367 |
| 12.9 | 2.13 | 24 | 0.102 | 0.217 |
| 12.8 | 2.05 | 30 | 0.127 | 0.26 |
| 12.7 | 2.1 | 26 | 0.11 | 0.231 |
| $\Sigma(\Delta T{\cdot}P_i)$: | | | | 2.048 |

Table 7

The probability of mean additional overheating (ΔT=T2–T2') in a dynamic mode during the 2014–2015 heating season

| T2–T2' | $N_t$ | $P_i$ | $(T2-T2'){\cdot}P_i$ | T2–T2' | $N_t$ | $P_i$ | $(T2-T2'){\cdot}P_i$ |
|---|---|---|---|---|---|---|---|
| 0 | 14 | – | – | 1.7 | 111 | 0.0569 | 0.0967 |
| 0.1 | 2 | 0.001 | 0.0001 | 1.8 | 107 | 0.0548 | 0.0986 |
| 0.2 | 3 | 0.0015 | 0.0003 | 1.9 | 99 | 0.0507 | 0.0963 |
| 0.3 | 8 | 0.0041 | 0.0012 | 2 | 112 | 0.0574 | 0.1148 |
| 0.4 | 7 | 0.0036 | 0.0014 | 2.1 | 124 | 0.0635 | 0.1334 |
| 0.5 | 7 | 0.0036 | 0.0018 | 2.2 | 117 | 0.0599 | 0.1318 |
| 0.6 | 22 | 0.0113 | 0.0068 | 2.3 | 109 | 0.0558 | 0.1283 |
| 0.7 | 33 | 0.0169 | 0.0118 | 2.4 | 85 | 0.0435 | 0.1044 |
| 0.8 | 39 | 0.02 | 0.016 | 2.5 | 96 | 0.0492 | 0.123 |
| 0.9 | 46 | 0.0236 | 0.0212 | 2.6 | 83 | 0.0425 | 0.1105 |
| 1 | 64 | 0.0328 | 0.0328 | 2.7 | 54 | 0.0277 | 0.0748 |
| 1.1 | 73 | 0.0374 | 0.0411 | 2.8 | 30 | 0.0154 | 0.0431 |
| 1.2 | 79 | 0.0405 | 0.0486 | 2.9 | 27 | 0.0138 | 0.04 |
| 1.3 | 86 | 0.0441 | 0.0573 | 3 | 16 | 0.0082 | 0.0246 |
| 1.4 | 97 | 0.0497 | 0.0696 | 3.1 | 8 | 0.0041 | 0.0127 |
| 1.5 | 99 | 0.0507 | 0.0761 | 3.2 | 1 | 0.0005 | 0.0016 |
| 1.6 | 107 | 0.0548 | 0.0877 | 3.3 | 1 | 0.0005 | 0.0017 |
| $\Sigma((T2-T2'){\cdot}P_i)$: | | | | | | | 1.81 |

As it can be seen from Table 9, the average difference between the temperatures T1 and T2 in the steady mode is the same for heating seasons 2014–2015 and 2015–2016. Accepting $\Sigma(\Delta T{\cdot}P_i)=2$ °C, the adjustments are made to the database of the heating season 2015–2016 to create a conventional temperature T2'.

Table 8

The probability of temperature T1 during the 2015–2016 heating season

| T1, °C | N | $P_i$ |
|---|---|---|
| 12.8 | 1 | 0.004 |
| 13 | 3 | 0.012 |
| 13.1 | 32 | 0.126 |
| 13.2 | 60 | 0.237 |
| 13.3 | 45 | 0.178 |
| 13.,4 | 29 | 0.115 |
| 13.5 | 23 | 0.091 |
| 13.6 | 28 | 0.111 |
| 13.7 | 14 | 0.055 |
| 13.8 | 10 | 0.04 |
| 13.9 | 7 | 0.028 |
| 14 | 1 | 0.004 |

Table 9

The probability of mean temperature ΔT=T2–T1 in a static mode during the 2015–2016 heating season

| T1 | ΔT=T2–T1 | N | $P_i$ | $\Delta T \cdot P_i$ |
|---|---|---|---|---|
| 13.1 | 2.13 | 32 | 0.133 | 0.283 |
| 13.2 | 2.06 | 60 | 0.249 | 0.513 |
| 13.3 | 2.04 | 45 | 0.187 | 0.381 |
| 13.4 | 1.88 | 29 | 0.12 | 0.226 |
| 13.5 | 2 | 23 | 0.095 | 0.19 |
| 13.6 | 2.03 | 28 | 0.116 | 0.235 |
| 13.7 | 2.11 | 14 | 0.058 | 0.122 |
| 13.8 | 2.12 | 10 | 0.041 | 0.087 |
| $\Sigma(\Delta T \cdot P_i)$: | | | | 2.037 |

Mean overheating temperature is $T_{ov}$=1.4 °C. The number of heating cycles with overheating is $N_t$=1849, the number of cycles without overheating is $N_t$=2. As shown in Table 10, the total share of the length of overheating periods in the heating season 2015–2016 is 0.0687 (6.87 %).

Compared with the previous heating season, the average overheating temperature reduced by 0.4 °C and the duration of overheating periods reduced by 7.25–6.87=0.38 %. The relative reduction in the length of overheating periods was (1–6.87/7.25)·100 %=5 %. Thus, lowering the set temperature by 1 °C had a positive impact on the efficiency of using stored heat.

Table 10

The probability of mean additional overheating (ΔT=T2–T2') in a dynamic mode during the 2015–2016 heating season

| T2–T2' | $N_t$ | $P_i$ | $(T2-T2')\cdot P_i$ |
|---|---|---|---|
| 0 | 2 | 0.001 | 0 |
| 0.2 | 5 | 0.003 | 0.0006 |
| 0.3 | 14 | 0.008 | 0.0024 |
| 0.4 | 17 | 0.009 | 0.0036 |
| 0.5 | 36 | 0.019 | 0.0095 |
| 0.6 | 46 | 0.025 | 0.015 |
| 0.7 | 64 | 0.035 | 0.0245 |
| 0.8 | 82 | 0.044 | 0.0352 |
| 0.9 | 72 | 0.039 | 0.0351 |
| 1 | 93 | 0.05 | 0.05 |
| 1.1 | 124 | 0.067 | 0.0737 |
| 1.2 | 134 | 0.072 | 0.0864 |
| 1.3 | 152 | 0.082 | 0.1066 |
| 1.4 | 160 | 0.087 | 0.1218 |
| 1.5 | 155 | 0.084 | 0.126 |
| 1.6 | 133 | 0.072 | 0.1152 |
| 1.7 | 121 | 0.065 | 0.1105 |
| 1.8 | 125 | 0.068 | 0.1224 |
| 1.9 | 89 | 0.048 | 0.0912 |
| 2 | 77 | 0.042 | 0.084 |
| 2.1 | 42 | 0.023 | 0.0483 |
| 2.3 | 36 | 0.019 | 0.0437 |
| 2.4 | 14 | 0.008 | 0.0192 |
| 2.5 | 12 | 0.006 | 0.015 |
| 2.6 | 4 | 0.002 | 0.0052 |
| 2.7 | 4 | 0.002 | 0.0054 |
| 2.8 | 1 | 0.001 | 0.0028 |
| 2.9 | 2 | 0.001 | 0.0029 |
| 3 | 1 | 0.001 | 0.003 |
| 3.4 | 1 | 0.001 | 0.0034 |
| $\Sigma((T2-T2')\cdot P_i)$: | | | 1.4 |

## 6. Conclusions

1. An experimental and research space heating system with a dynamic storage heater is introduced. The system contains a set of measurement tools, which allows studying the temperature distribution at several points simultaneously. This created the basis for collecting data on the storage

heater operation in real conditions for expanding the information on indicators of thermal processes in space.

2. Temperature measurement error in the range of 10...25 °C accounts for 6.8...2.8 %, respectively. The greatest errors in studies are from temperature sensors and the controller-logger unit, which records temperature values.

3. Since the 2014–2015 heating season and up-to-date, temperature has been recorded in the above-mentioned space heated with a dynamic storage heater. This provided 75.000 time-synchronized records of temperatures at different points in the space heated with a dynamic storage heater.

4. Based on the study of the temperature gradient at different values of temperature, which regulates a storage heater, it is revealed that the value of the set temperature can influence room overheating. The lower the set temperature, the lower the temperature gradient along the height of the space.

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