Improvement of methods for thermal energy metering in apartment buildings with a vertical heating system

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Abstract. The article briefly discusses the problems of heat energy metering in an apartment building. We mention the main types of metering devices, including heat cost allocators of different kinds. We describe the problems of thermal energy metering in a heating system with vertical heating contour. Also, we indicate the possibility of using the methods of mathematical physics for heat energy metering.

1. Introduction

In our time of constant growth of tariffs for all types of utilities, the problem of equitable distribution of utility bills between the owners of premises in an apartment building (AB) is more urgent than ever. The payment for gas, electricity and water supply for each owner is calculated relatively easily using individual metering devices. But bills for the most expensive utility service in Russia, heat supply, based on the calculation which may be far from fair.

If the building is equipped with a general building heat meter (GBHM), the amount of payment is determined in accordance with Russian Government Decree of 06.05.2011 No. 354 “On the provision of utilities to owners and users of premises in apartment buildings and residential buildings” (Decree 354) \[1\]. Heat consumption is distributed to all owners in proportion to the area of their premises. This regulatory document does not reflect such characteristics as the number and power of heating devices in the room, the actual temperature regime, and the volume of the room. Redevelopment has a similarly significant effect on the consumption of thermal energy in apartment buildings \[2, 3\], but Decree 354 doesn’t take into account the difference between ordinary and redeveloped apartments in the same building.

The amount of consumed thermal energy is calculated by the heat meter in accordance with the methodology of GOST R EN 1434-1-2011 standard \[4\] as

\[ Q_i = k(\theta_2 - \theta_1)V_i, \]

where \(Q_i\) is the amount of heat energy corresponding to the \(i\)-th time interval, \(V_i\) is the volume of the coolant taken into account by the flow meter during the \(i\)-th time interval, \(\theta_2\) is the temperature of the coolant at the inlet, \(\theta_1\) is the temperature of the coolant at the outlet, \(k\)
is the thermal coefficient depending on the properties of the coolant \[4\]. Accordingly, the heat energy that was given off during \(i = 1, n\) time intervals is calculated as

\[ Q = \sum_{i=1}^{n} Q_i. \]  

Trends in the construction market do not stand still. Since 2010, horizontal heating systems in AB have been actively used in Russia. Initially, this technology was used for elite and premium class housing, and since 2020, horizontal heating systems are increasingly found in economy class houses. With a horizontal heating system, it is possible to install a heat meter for each apartment and make accounting and accruals using the metering device individually.

According to the Levada Center, in 2004, 71% of the Russian population use a centralized heat supply and have a vertical heating system. So, they are actually deprived of the possibility of individual metering of heat energy. The solution to this problem can be heat cost allocators which can be installed directly on the radiator.

2. Types of heat cost allocators
Heat cost allocators consist of several temperature sensors (usually two) and a calculator. The device at regular intervals measures the temperature of the surface of the heater at one specific point and records the temperature difference between the surface of the radiator and the air in the room in the non-volatile memory. As a result, the readings of these heat metering devices correspond to the amount of heat given off by the radiator over the past period, measured in conventional units. However, heat cost allocators have several significant disadvantages.

First, the low accuracy class of the instruments. Because of this, the readings of a conventional heat cost allocator can only be taken into account when the heat cost allocators are installed in a significant number of premises (according to Decree 354, the share must exceed 51% of the owners).

Note that the calculation with consumers of thermal energy is carried out in gigacalories (Gcal). The calorie is a certain amount of energy that is needed to heat 1 gram of water to 1 degree. Secondly, the allocators display thermal energy not in kilowatt-hours (kW·h) or Gcals, but in conventional units with a few exceptions (see below). Therefore, it is necessary to install a calculator, in addition to the GBHM of thermal energy, that converts the readings into conventional units. The charges for heating is calculated according to the GBHM and individual allocators’ readings.

2.1. Allocators-evaporators
The allocators were created in 1917 as auxiliary devices for determining the consumption of thermal energy. Such devices initially consisted of a heat conductor with a liquid-filled ampoule, open for evaporation and attached to it. They were based on the principle of the dependence of the evaporation rate of a liquid on a change in temperature affecting it. These “allocators-evaporators” became widespread in Western Europe in the 1970s during the oil crisis and are used there to this day. The amount of evaporation is visually recorded on a graduated scale by the operator once a year, and the value, together with information about the heater, is manually entered into external calculation programs, where these readings are multiplied by correction factors obtained during laboratory tests, depending on the type of radiator, the method of fastening the allocators, etc. parameters.

These devices had many technical shortcomings. They could not take into account the nonlinear relationship between the temperature of the heater, its heat transfer and liquid evaporation, liquid evaporation outside the heating season, etc. The estimated value obtained after calculations had a significant error in relation to the actual heat consumption. Therefore,
these devices served exclusively to distribute the total cost of heating the house between tenants and apartment owners. Indeed, due to the absence of both measuring and computing components, such allocators were unable to read heat energy with a given satisfactory accuracy. Required services for the annual recalculation of individual readings for general metering devices using correction factors, which were produced by specialized billing companies.

### 2.2. Electronic allocators

The situation has changed dramatically with the production and mass introduction of electronic allocators (Fig. 1, Fig. 2) since the 80s of the last century. In contrast to “allocators-vaporators”, such devices now have measuring parts (built-in sensors for measuring the surface temperature of the heater and air), a microcontroller and a display. These devices operated from an autonomous power source (lithium battery) and had data archiving. Later, the devices had obtained the ability to remotely transmit data over a radio channel.

Now, describe the physical essence of measuring the amount of heat energy with allocators as in [5]. Initially, in the $i$-th time interval by the temperature on the surface of the heating device $\theta_{HS}$, the air temperature in the room $\theta_{RS}$, the so-called logarithmic excess temperature

$$\Delta \theta_i \approx k_{sys}(\theta_{HS} - \theta_{RS}).$$

(3)

The calibration coefficient $k_{sys}$ depends on the design of a particular valve and is required to take into account the deviation of the coolant and air temperatures obtained during measurement from the actual ones. We calculate the thermal power in the $i$-th time interval with the duration $\Delta t$ as

$$Q_i = \dot{Q}_N(\Delta \theta_i)^n \Delta t.$$

(4)

Here $\dot{Q}_N$ is the nominal power of the heating device, and $n$ is the thermal exponent. These parameters are determined and published by the device’s manufacturer after testing under standard conditions, for example, following the EN 442-1&2:2014 “Radiators and convectors” standards. Finally, as in the case of a heat meter, the heat output over a period of time is calculated as the sum of (1). However, it is difficult to use a common allocator for an accurate calculation of the consumed heat energy as the values of the parameters $\dot{Q}_N$, $n$ and $k_{sys}$ vary depending on the temperature of the coolant. Also, these parameters can change on covering the device with towels or decreasing the volume of the incoming heat carrier using a valve.

### 2.3. Heat calculators

More recently, a new subclass of heat cost allocators has appeared – heat calculators. These are devices of significantly higher accuracy than an ordinary allocator and can display readings in kВ·h. These readings do not need to be corrected using the other calculators’ readings in the remaining apartments of the AB. Accuracy is achieved due to the fact that the manufacturers of this subclass of allocators have a database of correction coefficients calculated for the wide set of radiators during tests by the manufacturers of calculators. These coefficients are different for different values of the temperatures difference $\theta_{HS} - \theta_{RS}$. Instead of the ratio (4), the heat calculator uses the ratio

$$Q_i = \dot{Q}_N(\theta_{HS} - \theta_{RS})^{n_{korr}(\theta_{RS}\theta_{RS})}\Delta t k_{korr}(\theta_{HS} - \theta_{RS}),$$

where $n_{korr}(\theta_{HS} - \theta_{RS})$ is the thermal exponent corrected for the given value of the temperature difference between the surface of the radiator and the air $\theta_{HS} - \theta_{RS}$, $k_{korr}(\theta_{HS} - \theta_{RS})$ is the device coefficient with corrections for the given value of the difference in temperature between the surface of the device and the air $\theta_{HS} - \theta_{RS}$.

The market leader and the creator of the first device of this class in this area is the Techem group of companies, which produces heat energy calculators FHKV (data III, radio4) with two
Figure 1. Scheme of a heat cost calculator or a heat cost allocator with two sensors (2, 3) installed on a heating device.

Figure 2. General view of the installed heat cost allocator on the radiator.

sensors. The calculators themselves perform all necessary calculations, which does not violate the principle of uniformity of measurements and calculations. All FHKV devices (data III, radio4) are manufactured in accordance with the Russian Federal Law “On Ensuring the Uniformity of Measurements” of 26.06.2008 No. 102-FZ. Also, they are manufactured in full compliance with the standard EN834:2013 “Heat cost allocators for the determination of the consumption of room heating radiators. Appliances with electrical energy supply”.

FHKV calculators (data III, radio4) are produced serially with two temperature sensors calibrated in production. At the same time, various algorithms for recognition of manipulation and protection against unauthorized access and distortion of measurement results are placed into the memory of each device during manufacture. Each calculator is reliably sealed during installation and further opening is impossible without damaging the seal. Also, the calculators are equipped with a built-in disassembly detection sensor that detects unauthorized access. The date and time of opening are instantly recorded in the memory of the calculator with an error code and transferred to the accounting system.

If the calculator is covered with a rag, foil, or the air temperature sensor is heated by an external source of thermal energy, the calculator recognizes such a sharp change in temperature (increase in air temperature) and automatically switches to the “single sensor” mode, that is, only the measured temperature is used to calculate the temperature difference and thermal energy heater, and the air temperature is estimated at 16°C. Thus, an attempt at manipulation leads to additional costs for the intruder, since in this case the calculator calculates a higher heat consumption based on a lower air temperature.

3. Discussion

Unfortunately, even modern allocators have one major drawback: measuring the temperature only in the immediate vicinity of the radiator gives distorted picture of the real thermal energy consumption.

Receiving heat from a radiator consists of three components. The first is heat transfer which is the process of transferring heat from a heated coolant to the air in the room. Physically, this is represented as heat transfer from three media, water-metal-air. The second is convection.
is a type of heat exchange in gaseous substances, in which warm air in motion mixes with colder air and gives off part of its heat. On the example of a radiator, this happens as follows: the air in the room, warming up at the radiator wall, goes up, displacing the colder air (with a greater mass down), then the cold air heats up and rises, and the cooled air (with a greater mass) goes down. It is convective flows that do not give us the right to talk about a constant and equal temperature in a room. Temperature distribution in radiator heating has long been studied and widely illustrated graphically (Fig. 3).

Figure 3. Room temperature distribution (from https://saulesbroliai.lt/tai-kas-geriau-grindys-ar-radiatoriai/).

The third type of heat transfer is radiation. This is the transfer of heat from one body to another with the help of heat rays. In the case of a radiator, heat rays behave as follows. They fall on objects or people in the room, and are converted into thermal energy of heat.

For improvement of heat cost allocators, all transmission methods should be taken into account. This can be done by introducing correction factors, determining the geometric dimensions of the room for specific models, or by measuring the temperature at various points in the room.

3.1. Issues of the heat metering in a vertical heating system

With a horizontal heating system, a certain part of the thermal energy into the room comes from openly laid pipes. Heat transfer from pipes \( Q_{tr} \), W, is determined as the sum of heat transfer from all pipes of various diameters, laid in the premises, according to the formula

\[
Q_{tr} = \sum_i q_{itr} \cdot l_{itr},
\]

where \( q_{itr} \) is the specific heat transfer from horizontal or vertical pipe sections, Wt/m; \( l_{itr} \) is the length of horizontal or vertical pipe sections, m. Specific heat transfer from open pipes can be determined by calculation, or according to the applied tables.

There are two solutions to the problem here. The first is to determine the heat transfer by calculation and fix the calculated value for each living room. The second is to ignore heat transfer. In this case, part of the heat energy will be considered as general building needs and will be proportionally distributed over the area or volume of the premises. In any case, both options require careful study and legislative regulation.

The next issue that arises when using heat cost allocators is the heat consumption for heating common areas (CA) which are stairs, entrances, elevator halls, etc. Depending on the project, heating devices can be installed in the CA, or vice versa, the premises are not heated.
The most interesting issue is heat transfer between heated and unheated rooms of an apartment building. The temperature regime depending on the room may differ significantly. For example, the temperature of unheated flights of stairs is about 10°C, and the temperature in the apartment rises to 26°C. A similar situation is observed with the basement and the technical floor, here the temperature difference can be even more significant.

For the convenience of understanding the physical process, consider a 4-storey apartment building. Figure 4 shows a cross-section of a building.

![Figure 4. Cross-section of an AB.](image)

It can be conditionally divided into 4 temperature zones: living quarters, common areas, attic, basement. In the residential area, in turn, we will select 4 rooms and describe their sources of heat loss. For all 4 rooms, windows and external fences will be a natural source of outgoing heat; in this example, we will consider them constant and the same for all rooms.

For room No. 1, the main heat loss will be through the floor and walls bordering the flight of stairs. For premises No. 2 and No. 3 only the border with the CA. With a centralized heating system, the difference between the heated rooms is not significant. However, for apartment heating, where it is possible to regulate and turn off heating, a heat flow occurs between such rooms with a direction from cold to warm, which must already be taken into account. For room 4, the situation is similar to the first one: heat loss through the attic and the wall adjacent to the CA. Thus, all of the listed premises have a different heat transfer mode, and therefore, when taking into account the costs of thermal energy, they cannot be considered the same.

In order to make each apartment non-volatile, we should calculate two parameters. The first is the minimum room temperature during the heating season. The concept is understood as the value of the temperature in degrees target during the heating period, which the owners are obliged to provide regardless of the use of the premises. This concept will allow adjusting of the
thermal regime in premises bordering on non-residential and commercial premises.

The second one is the required thermal resistance of internal walls and interfloor partitions. Reducing the thermal conductivity of walls will significantly reduce additional heat loss.

K. F. Fokin proposed an expression that determines the temperature of an unheated room [6, P. 51]:

\[
t_x = \frac{t_1k_1\cdot t_2k_2\cdot t_nk_n\cdot F_n + W_{ct\_air} + Q_0}{k_1\cdot F_1 + k_2\cdot F_2 + k_n\cdot F_n}
\]  

where \(t_x\) is the air temperature in the unheated room, \(t_1, t_2, t_n\) the air temperature in the adjacent rooms, \(F_1, F_2, F_n\) are the area of the fences, \(W_{ct\_air}\) is the value that determines the amount of heat for the heated air coming through infiltration, \(Q_0\) - additional sources of heat.

Thus, we determine the temperature in unheated rooms, we can determine the heat flow through the fences.

3.2. Using the mathematical physics

Book [7, P. 406] describes the coordinated problem of heat exchange by radiation and heat conduction as the initial-boundary problem in the domain \(\Omega\) with the boundary \(\Gamma = \partial \Omega\):

\[
-\sum_{\alpha=1}^{2} \frac{\partial}{\partial x_\alpha} \left( k(x) \frac{\partial u}{\partial x_\alpha} \right) = f(x), \quad x \in \Omega,
\]

\[
f(x) = g(x), \quad x \in \Gamma,
\]

\[
k \frac{\partial u}{\partial n} + \sigma_1(x)(u - g(x)) + q(x) = 0, \quad x \in \gamma,
\]

\[
q(x) - \kappa(x) \int_{\gamma} G(x, \xi) q(\xi) d\xi = \sigma_2(x)u^4(x, u), \quad x \in \gamma,
\]

where \(\gamma \subseteq \Gamma\) is the radiating part of the boundary, \(\sigma_1\) is the coefficient of convective heat exchange, \(\sigma_2\) is the emissive power of the body, \(q\) is the flux of the radiation, \(u\) is the body temperature, \(0 < \kappa < 1\) is the reflection coefficient, \(g\) is the external temperature. The kernel \(G\) is defined as

\[
G(x, \xi) = \frac{1}{||r(x, \xi)||} \cos(n(x), r(x, \xi)) \cos(n(\xi), r(x, \xi)),
\]

where \(||r(x, \xi)||\) is the distance between points \(x\) and \(\xi\), \(r(x, \xi)\) is the line segment with endpoints \(x\) and \(\xi\).

Using the similar equation can be used for the precise description of the temperature in any point of the apartment.

4. Conclusion

Heat cost allocators register the amount of thermal energy emitted by individual radiators. Most heat cost allocators register the amount of heat energy with a significant error of up to 40-60%.

Therefore, specialists have introduced the concept of a conventional dimensionless unit of thermal energy given off by a radiator. In this case, the accuracy and fairness of calculations for heating are ensured only when 100% of the premises in the apartment building have allocators.

Heat cost allocators with two sensors for the surface temperature of the radiator and the temperature of the air in the room, with the table of correction coefficients stored in the internal memory, can calculate the thermal energy in kW·h with an error of 5-6%. A heat cost allocator with an accurate calculation of the amount of thermal energy given off by a radiator is called a heat calculator by specialists and belongs to individual heat metering devices.

It is necessary to improve heat cost allocators to account the thermal energy transmitted by openly laid pipes, as well as by walls from other rooms.
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