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# Energy economic suitability of the use of "air-air" recuperators in the climatic conditions of the republic of Armenia

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**Abstract.** The issues of energy saving in buildings are considered by using recuperators to save heat and cold, lost when removing air from the buildings space and transferring some of the energy to the fresh air that is supplied into the premises. Such heat exchangers can be a part of the mechanical ventilation system, as well as stand alone and carry out partial (due to heat exchange) or complete heating of fresh air (by using a heat transfer agent or an electric heater). Depending on the place of application and the recuperator type, they can have different energy efficiency or thermal efficiency, price, and respectively, energy economic indicators and payback period. Often, the developers and plants, the manufacturers go on partial deterioration of these indicators to reduce the product price, suggesting to use simpler structures, in particular, recuperators of "air-air" type with a different number of pipes in the heat exchanger. In the present material, the methods of calculation of multi-pipe recuperators for utilization of heat of exhausted air, having the simplest structures, are given. The areas of expedient use in various climatic conditions of the Republic of Armenia are determined. The criteria are the given expenses, fuel economy, their manufacture costs.

## 1 Introduction

The issue of reducing the primary energy for the needs of the systems to create microclimate in residential buildings occupies a significant place in the designs of increasing energy efficiency of systems and installations, consuming organic fuel, since up to 40% of the world's fuel is consumed for these needs. Currently, the widespread use of hermetic, energy-saving "euro-windows" significantly worsens the quality of the indoor air, because unfavorable sanitary-hygienic conditions are created due to the lack of infiltration of air through the windows, the "euro-windows" do not provide the required oxygen quantity, and the amount of CO2, radon and relative humidity increases, and favorable conditions are created for the development of fungi, harmful bacteria, etc. The latter

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negatively affects people's health. Old windows provided infiltration of fresh air, especially when they were naturally ventilated. The fuel consumption for the needs of the micro-comfort creation systems can be reduced by the recuperation of heat and cold of the air which is being removed from the room, with the use of heat recuperators, which allow to keep the cleanliness and thermal regime of the indoor air in the premises by organizing a joint process of fresh outdoor air inflow and its heating due to the removed, exhaust air. The latter can be arranged by means of centralized mechanical ventilation, when the supply air pipe is crossed with the exhaust pipe by means of a plastic recuperator of various capacities. In this scenario, it is possible to save electricity or any type of fuel for heating appliances, which is about 40 ... 50%. In this case, these recuperators can have different designs.

## 2 Literature study

For the creation of the necessary comfort inside the building and for the energy-efficient use of heat and cold, heat recuperators should be used in order to recuperate the energy of the air, which is being removed from the room and to transfer it to the fresh air [1.2]. This process can be centrally organized by means of mechanical ventilation [3.4.5.6], when the supply air pipe is crossed with the exhaust pipe by means of a plastic recuperator of various capacities. One of the solutions for a detached house can be the use of the plastic recuperator, described in [7], when, on the one hand, the hot exhaust air is supplied to the recuperator and on the other hand- the cold fresh air. Those are supplied to the recuperator with the help of the system of exhaust and supply ventilation. The rotor recuperators [7] have also been applied, when the air stream inflow and outflow are carried out due to the blades. The system consists of one to two driving rotors, depending on the model. Externally, the installation looks like a cylindrical barrel with a drum. As the air is evacuated from the room and the cylindrical box is heated, the atmospheric mass is being collected. In [8,9] it is given information on plastic (with steel and paper plates) and rotor recuperators of local-central purpose, combined with the ventilation system. However, not all the buildings have a mechanical ventilation system, but all the premises have natural ventilation. In such cases, the recuperation system can be used, applying local-central heat pumps (HP), as described in [10]. In order to utilize the heat of the air, removed from the building premises, negative temperatures are created in the HP evaporators, at the expense of which the exhaust air can cool down to ambient air temperature, and the utilized heat is used to generate useful heat for the needs of the local-central system. However, in the conditions of Armenia, the premises are not always heated by the building heating system. With wide gas supply of urban areas, republic settlements and authorization of the authorities, depending on the social well-being of residents, small-capacity inter-apartment boilers (up to 30 kW), gas furnaces with turbo and natural draught, electric heaters serve as heat sources, because in [15.16] it is proposed such a structure, when the necessary volume of fresh air is provided the internal heating systems of buildings are out of order for a long time. This means that the application of the mentioned system of utilizing the heat of exhaust air using a HP is practically impossible or it requires additional capital investments by the state and the residents. This is confirmed by the practice of adoption of local-centralized systems with heat-cogeneration units as a heat source on the base of internal combustion gas engines.
Many methods are suggested for getting out of this state by applying "warm ventilating windows", special slots for the organization of unorganized ventilation and air heat and mass exchange, etc. However, unheated air enters the room, which creates discomfort, the heating load increases, etc. It is therefore more practical to use heat utilizers of exhaust air in the form of "air-air" recuperators with a simple structure and low price. In this case, it is

possible to transfer the heat of the exhaust air in fresh form and reduce the heat load of the heating systems in winter and the cooling in summer. One of the solutions is the use of indoor air recuperators of "air-air" type [11 ... 14], when the partial heating of fresh air, supplied to the room, is carried out in two - and more pipe "pipe in pipe" heat exchangers due to the air removed from the room. Partly, such recuperators become a part of the ventilation system. They are mainly installed inside the wall and in order to provide the necessary air pressure they can be supplied with low power ventilators, and for subsequent heating of the air with an additional electric heater- with input and output adjustable grids. All this leads to an increase in the energy efficiency of the recuperator, but its price rises.
In order to reduce the price, due to which the energy efficiency of the recuperator is simultaneously reduced, , which is partially, as far as possible, heated at the expense of the extracted air. Subsequent heating of the air is realized due to the internal air.

### The main conclusions from the studied literature sources and the elaboration of the purpose of the study

One of the solutions of this state is the use of indoor (inter-apartment) recuperators of the "air-air" type, which will ensure the inflow of the necessary volume of fresh air, preheating it at the expense of the extracted air. For the utilization of the heat of the extracted air, from the energy-economic point of view, local recuperators, installed inside the walls, with small energy indicators, but low prices, may turn out to be the most profitable ones. Based on this, the purpose of this article is to develop methods and mathematical models of recuperators that have the best energy and economic indicators, in particular, for specific climatic and price conditions of the RA. Besides the energy saving, the use of these devices will ensure the welfare and safety of people, as they will ensure the supply of fresh air into the rooms, especially in winter season. If during the transition and summer seasons, depending on the inhabitant's will, the fresh air volumes exceed the sanitary-hygienic norms many times due to high temperatures of the outdoor air, leading to large heat losses and internal heat releases, harmful smells, etc., during winter season, the inhabitant spends a significant amount of electricity or natural gas to create a normalized, and sometimes lower indoor temperature. The state of air in the rooms deteriorates when using inter-apartment gas boilers, gas furnaces, electric fryers, water heaters, etc. As indicated in [15], such devices can utilize from 20 to 50% of the heat of the exhaust air, but they have a high price and, in the RA conditions, are not affordable for many residents of apartment buildings. It is required to use cheaper, although inefficient, types of recuperators of local production and made from local materials. To develop simpler "pipe-in-pipe" recuperators (without pipe ribbing), appropriate calculation methods should be developed, based on well-known methods of calculation of such devices for stationary heat transfer processes, as described in [17.18].

## 3 Methods

When the fresh air flows through the external pipe, because of natural draught, and the extracted air flows through the internal one (single or multi-pipe), as indicated in [19], the thermal efficiency may serve as energy characteristic of such recuperators, determined by the following formula:

$$\eta^{i}{}_{p.} = \frac{t_i - t_u}{t_f - t_u}, \tag{1}$$

where $t_i, t_f$ - are the temperatures of fresh and exhaust airs before and after the recuperation, $t_u$ - is the temperature of the outdoor air.

However with the value $\eta^i{}_{p.}$ it is impossible to determine the average-seasonal values of the thermal efficiency. It is impossible to determine the average seasonal values of the thermal efficiency considering the temperature-hours of the given month and season, with the subsequent determination of the utilized heat, as well as the fuel equivalent of the recuperator, consumed in a local or inter-apartment gas boiler, gas furnace, electric heater, etc. used by the residents. These values are necessary to determine the economic parameters of the recuperator. In order to determine the average seasonal thermal efficiency, considering the temperature-hours of each month and season, the following formula is proposed:

$$\eta_{p.}^{cp.c.} = \frac{\sum\limits_{j=1\div n} \eta_{p.}^{cp.c.j} \cdot z^{m.}_{t^j_{n.w.}}}{\sum\limits_{j=1\div n} z^{м.}_{t^j_{n.w.}}}, \tag{2}$$

where $\eta_{p.}^{cp.c.j}$, $z^{м.}_{t^j_{n.w.}}$ - thermal efficiency of the recuperator and quantity of hours of temperatures $t^j_{н.в.}$ for the given $j$ month.

The mathematical model, the algorithm are elaborated, for determining the utilized heat by the recuperator of this type when the airflow in the apparatus is direct and counterflow. Regarding the direct flow, the amount of this heat is determined by the formula:

$$Q^j_{ym.m} = \frac{t_{yд.в.} - t_{cв.в.}}{R_\Sigma}, \tag{3}$$

As during the counterflow the following temperatures are given- $t_{yд.в.}, t_{cв.в.}$, for the determination of this heat the following formula is proposed:

$$Q^j_{ym.m} = \frac{(t_{yд.в.} - t_{cв.в.})A}{1 + AR_\Sigma}, \tag{4}$$

where - $V_{cв.в} \cdot c^{м.}_{cв.в.} \cdot \rho^{м.}_{cв.в.} = A,$ (5)

$R_\Sigma$ - total heat resistance of the recuperator.

The thermal resistance of pipes for the exhaust air, with a stationary process of thermal conductivity in its walls, is determined for cases with an infinite rod in the amount $n_{mp.}$ pcs and under the condition $R_{yд.в.} \lhd R_1, n_{mp.} \rhd 1$, by the following formula:

$$R_{mp.} = \frac{1}{2 \cdot 3.14 \cdot L \cdot \lambda_{mp.}} \left[ \ln \frac{R_{cв.в.}}{R_1} + \frac{1}{n_{mp.}} \cdot \ln \frac{n_{mp.} \cdot R_{yд.в.}}{R_1} \right], \tag{6}$$

$R_1$, $R_{cв.в.}$, $R_{yд.в.}$ - radii of the pipe axis for the removal of fresh, exhaust air, m.

If more than two pipes are required to remove air, the volume flow of air in one pipe will be: $V_{уд.в.}^{1тр.} = \dfrac{V_{уд.в}}{n_{тр.}}$, where $n_{тр.}$ - the quantity of pipes for the air removal. This means that the total heat resistance of the recuperator changes due to the change in the mode of movement of the exhaust air. This will lead to the criteria of Nusselt and the coefficient of heat transfer $\alpha_{св.в.}, \alpha_{уд.в.}$. The first one, according to [18], is determined by the following formula:

$$K = 0{,}021\mathrm{Re}_{в.}^{0.8},\ K = \overline{Nu}_{в.}\,\mathrm{Pr}_{в.}^{-0.43}\left(\mathrm{Pr}_{в.}/\mathrm{Pr}_{ст.}\right)^{-0.25}, \quad (7)$$

According to the graphs given in [18], for example, for three pipes, we have:

$$\overline{Nu}_{в.} = 6K\cdot 0{,}021\mathrm{Re}_{в.}^{0.8}\,\mathrm{Pr}_{в.}^{0.43}\left(\mathrm{Pr}_{в.}/\mathrm{Pr}_{ст.}\right)^{0.25}\varepsilon_l, \quad (8)$$

Defining the value $\overline{Nu}_{в.}$ of the fresh and exhaust air, it is possible to define $\alpha_{св.в.}, \alpha_{уд.в.}$, and through them- also the value $R_{\Sigma}$ [17].

According to this technique, an algorithm and a computer program for Excel have been drawn up, which make it possible to calculate the heat engineering parameters and the seasonal heat efficiency of the recuperator at given sizes and number of air removal pipes. Then, based on these calculations, you can determine the heat, taken from the air, being removed, the amount of fuel, saved per season, if the mentioned amount of heat is generated in the boiler. Calculations were carried out at the norm of fresh air 0.0136 m3 /s.person, under temperatures of the exhaust and fresh air of 18 or 19 $^{o}C$, outdoor average monthly temperature of $t_{мес.}^{i}$ for the current month, defined by the data of meteorological services. The climatic conditions of a number of RA cities are considered: Yerevan, Sevan, Hrazdan, Dilijan, Artashat, Vanadzor, Kapan, having different monthly average outside air temperatures and degree- hours. The temperatures of the exhaust and the indoor air are adopted: $t_{вн.в}/t_{уд.в.}^{вых.} = 20/19{,}19/18\ ^{o}C$. The geometric sizes of the recuperator: $L = 1{,}4$ m, at one pipe for the exhaust and fresh air: $d_{уд.в.} = 0.1, d_{св.в.} = 0.147$ m, at three pipes: $d_{уд.в} = 0{,}04;$ $d_{св.в.} = 0{,}128,$ $\delta_{ст.} = 0{,}0004,$ $R_1 = c\dfrac{d_{св.в.}}{2}, c = 0.875 \div 1.125$ m, at eight pipes: $d_{уд.в.} = 0{,}032;$ $d_{св.в.} = 0{,}1405$ m, $\delta_{\text{ст.}} = 4\,мм$ $R_1 = c\left(\dfrac{d_{св.в.}}{2} - 5/8\cdot d_{уд.в.}\right),$ $c = 1$. As pipe materials are taken steel sheet, covered with a layer of zinc with a coefficient of thermal conductivity $\lambda_{ст.л.ц.} = 52\,Вт/м..град.$ .

The table contains technical data of various recuperators for the climatic conditions of a number of cities in the Republic of Armenia.

From the table it follows that with a two-pipe recuperator the highest value of thermal efficiency was obtained for the climatic conditions of the city of Kapan, the degree-hours of which are the smallest, and then for other cities, as the degree-hours increase. For the cities of Sevan and Hrazdan, which have the highest degree-hours, the value of the thermal efficiency is the lowest. The mentioned values of direct-flow recuperators have the opposite meaning.

With three-pipe recuperators, the values of thermal efficiency for the climatic conditions of these cities vary from 0.2869 to 0.2918. This means that, due to the increase in the number, along the perimeter of the installed pipes of exhaust air, the thermal efficiency increases by 2.3 times, which indicates the thermal and technical suitability of the measurement. But when using four-pipe recuperators, the thermal efficiency increases, on average, by 4%. This is a consequence of the increase in one pipe and the change in the total thermal resistance, which for the three-pipe recuperator is 0.1412, and the four-pipe-0.1334, or decreases by 5.8%, as the heat transfer coefficients change in different ways.

$$\alpha_{уд.в}^{чет.тр.} = 44{,}96; \quad \alpha_{св.в.}^{тр.тр.} = 45{,}38,$$

$$\alpha_{уд.в.}^{чет.тр.} = 14{,}96; \quad \alpha_{св.в.}^{тр.тр.} = 18{,}81 \text{ W/m2.degree.}$$

From the results in the table it follows that the increase in the number of pipes from 3 to 8 leads to an increase in thermal efficiency on average by 36.5%, because the heat efficiency of the recuperator depends on the degree-hours of the mentioned cities, as well as on the number of pipes of the recuperator. The latter determines the overall dimensions, manufacturing technology, material base and technical and economic indicators of the recuperator.

For the optimization of the mentioned indicators, the character of the change in the heat efficiency of the recuperator has been studied, depending on various factors. At first, the three-pipe recuperator is considered in detail. First of all, the effect of the used pipe material is considered: multilayer cardboard, galvanized metallic sheet, brass, and also the influence of the radius $R_1 = c\frac{d_{св.в.}}{2}$ (similar to the eight-pipe one, represented in the fig. 1). Calculations have been carried out for the climatic conditions of Vanadzor, which for most of the regions of the Republic of Armenia has typical monthly average temperatures and degree-hours for the winter season.

Calculations have been carried out in order to determine the thermal efficiency of the recuperator, and based on them, the graphs (see fig. 2), from which it follows that $R_1 = c\frac{d_{св.в.}}{2}$ and the applicable materials have the greatest influence on the thermal efficiency.

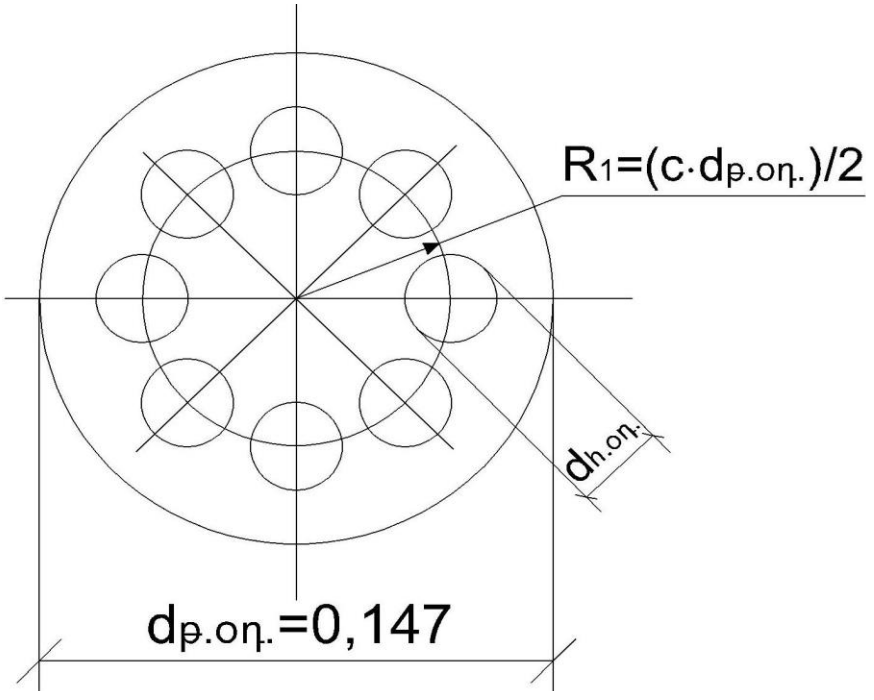


**Fig.1**. Eight-pipe recuperator of "pipe in pipe" type

In particular, for the multilayer cardboard the latter is 3.1 times smaller than when applied on the galvanized sheet.

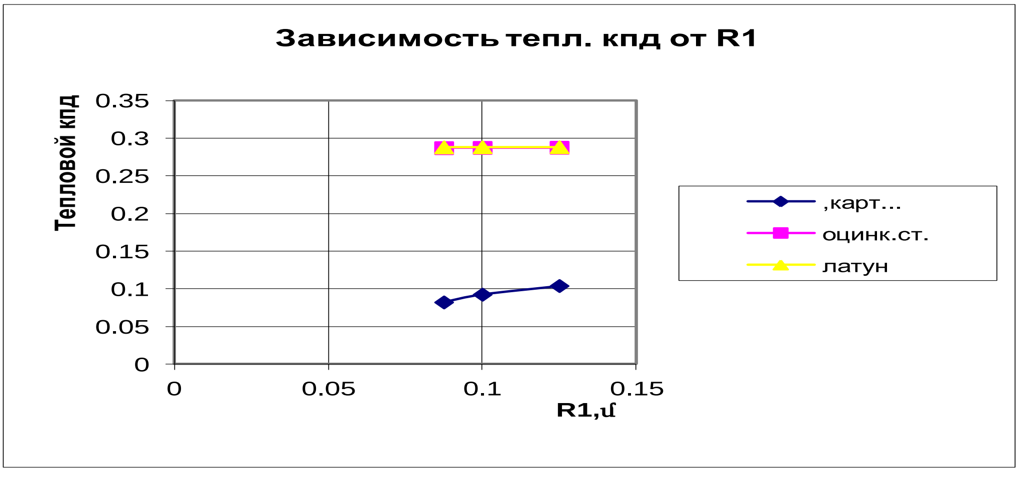


**Fig.2.** The change of the thermal efficiency of three-pipe recuperator, depending on $R_1 = c\dfrac{d_{св.в.}}{2}$ (under canonical arrangement of pipes for air removal), pipe dimensions and used materials. $d_{св.в.} = 0.1\,м, R_1 = c\dfrac{d_{св.в.}}{2}, L = 1.4\,м$, $\lambda_{м.с.к.} = 0.13;\ \lambda_{оц.л.} = 52;\ \lambda_{лат.} = 110$ W/m.degree).

However, while passing from the galvanized sheet to brass, although the coefficient of thermal conductivity in this case increases 2 times, the thermal efficiency changes insignificantly. This means: for manufacturing such recuperators, the used materials should have low price and should be available in the market, the recuperators have a simple manufacturing technology, and there is an appropriate machine/tool park at the production sites. As the production of the recuperator from galvanized pipes is more technological, the latter will be easy and will have a low price, it means that this material should be used. The thermal efficiency depends also on the radius $R_1 = c\frac{d_{св.в.}}{2}$ and along with the increase of $c = 0{,}875\ldots\ 1.125$, for the multi-layer cardboard the latter increases by 12.5 ... 26.5%. Such change, while using metals, is insignificant.

Similar calculations were made when the length of the pipes is increased. The thermal efficiency, along with the recupertaor length increase, linearly increases, because the surface of heat exchange increases, and the increase in the number of pipes leads to an increase in the thermal efficiency, however it is necessary to determine the optimum number of pipes depending on the energy and economic parameters - on the given costs, payback period of the recuperator, etc.

From the condition of the expediency use of the recuperator we have the following equality:

$$C^{к.}_{т.с.} \geq (E_н + k_{рен.})1.4K_{р.}, K_{р.} \leq \frac{C^{к.}_{т.с.}}{1{,}4\cdot(E_{н.} + k_{рен.})}\ , \tag{9}$$

where $C^{к.}_{т.с.}$ - annual saving of fuel in the boiler because of the use of the recuperator, USD/year, $E_н, k_{рен.}$ - normative coefficients of capital investments and renovation, $1.4K_{р.}$ - capital investments on the manufacturing and installation of the recuperator, USD.

The results of the calculations show that for the climatic conditions of the city of Vanadzor for three-, four- and eight-pipe recuperators, the annual heat savings and the corresponding fuel component in the gas boiler, at the natural gas price of 326USD /1000 m2, will be respectively 366.3, 381, 501.4 kW. h / season, 43.8, 45.6, 60,7m3 / season and 14.3, 14.9, 19.8 USD/ season. In the result, we have:

$$K^{тр.тр.}_{р.(3тр.)} \leq \frac{C^{к.}_{т.с.}}{1{,}4\cdot(E_{н.} + k_{рен.})} = \frac{14.3}{0{,}26\cdot 1{,}4} = 39.3,$$

$$K^{тр.тр.}_{р.(4тр.)} \leq \frac{14.9}{0{,}26\cdot 1{,}4} = 40.9,$$

$$K^{тр.тр.}_{р.(8тр.)} \leq \frac{19{,}78}{0{,}26\cdot 1{,}4} = 54.34, \qquad ам.дол./сез.$$

In the recuperator the specific capital investments on one pipe are:

$$k_{3тр.}^{рек.} = \frac{K_{р.(3тр.)}^{тр.тр.}}{n_{3тр}} = \frac{39.3}{3} = 13.1,$$

$$k_{4тр.}^{рек.} = \frac{K_{р.(4тр.)}^{тр.тр.}}{n_{4тр}} = \frac{40.9}{4} = 10.2,$$

$$k_{8тр.}^{рек.} = \frac{K_{р.(8тр.)}^{тр.тр.}}{n_{8тр}} = \frac{54.34}{8} = 6.8, \qquad ам.д./шт.сез.$$

It follows from the obtained result that the capital expenses on the four-pipe recuperator, in comparison with the three-pipe, increase by 1.6 USD, however, the production of the device becomes difficult. The price of one pipe in the recuperator exceeds by 2.9USD or by 28.4%, that is, it is more expedient to apply the four-pipe recuperator. Comparing the four- and eight-pipe ones, we get savings of 3.4 and 50.5% per pipe, which means: from the compared options, it is expedient to use the eight-pipe one if the specific capital investments will not exceed the obtained value - 54.34 USD/season. This means that an increase in the number of pipes leads to an increase in energy suitability, however, the final conclusions should be made based on specific figures.

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| Denomination of the value | Heat, taken by recuperator | Heat, taken in recuperator from the indoor air | Temperature of the fresh air at on the exit from the recuperator (in design conditions) | Average seasonal heat efficiency of recup. | Degree-hours (winter regime) |
|---|---|---|---|---|---|
| | | Total taken heat | | | |
| Value / city | $\sum Q^{рек}_{сез.}$, kWh/seas. | $\sum Q^{вых}_{сез.}$ | $t^{рек.}_{сз.в} / t^{вх.}_{сз.в.}$ °C | $\eta^{ср.с.}_{рек}$ | $(t_{вн.в} - t^{j}_{ср.н}) \cdot z^{j\ рек}_{нес}$ Degree -hours |
| | | $\sum\sum Q^{сум}_{сез.}$; kWh/seas. | | | |
| Yerevan | 141.54 | 182.881 | -11.74 | 0.1253 | 68401.4 |
| | | 324.42 | -6.28 | | |
| | 324.351 | 129.898 | -6.188 | 0.2870 | |
| | | 454.25 | -2,29 | | |
| | 442.478 | 121.908 | -2.56 | 0.3914 | |
| | | 564.386 | 1.1 | | |
| Sevan | 218.3 | 325.9 | -15.27 | 0.1248 | 114640.8 |
| | | 544.2 | -9.05 | | |
| | 554,0 | 219.5 | -9.04 | 0.2913 | |
| | | 773.5 | -4.73 | | |
| | 717,9 | 197 | -5.43 | 0.391 | |
| | | 914.9 | -1.48 | | |
| Vanadzor | 169.3 | 218.8 | -11.74 | 0.1253 | 81846.3 |
| | | 388.0 | -6.28 | | |
| | 387.783 | 155.42 | -6.19 | 0.2871 | |
| | | 543.1 | -2.29 | | |
| | 499.987 | 137.607 | -2.93 | 0.392 | |
| | | 637.593 | 0.63 | | |

| | | | | | |
|---|---|---|---|---|---|
| Kapan | 123.7 | 160.1 | -6.44 | 0.1256 | 60354.4 |
| | | 283.8 | -1.88 | | |
| | 265. 5 | 106.4 | -2.10 | 0.2878 | |
| | | 371.8 | 1.04 | | |
| | 362.4 | 99.9 | 0.81 | 0.3926 | |
| | | 462.3 | 3.77 | | |
| Artashat | 141.5 | 182.9 | -11.73 | 0.1253 | 69463.4 |
| | | 324.4 | -6.28 | | |
| | 311.9 | 124.8 | -8.65 | 0.2871 | |
| | | 436.7 | -4.55 | | |
| | 329.8 | 132.1 | -8.38 | 0.2869 | |
| | | 461.9 | -4.17 | | |
| Hrazdan | 230.4 | 313.4 | -15.27 | 0.125 | 110224.8 |
| | | 543.8 | -3.65 | | |
| | 506.1 | 200.4 | -9.31 | 0,2918 | |
| | | 706.5 | -5.12 | | |
| | 687.2 | 188.6 | -5.43 | 0.3913 | |
| | | 875.8 | -1.48 | | |
| Dilijan | 161.3 | 222.7 | -9.09 | 0.1254 | 78277.6 |
| | | 384.0 | -3.9 | | |
| | 348.1 | 139.4 | -4.28 | 0.2875 | |
| | | 487.5 | -0.82 | | |
| | 475.067 | 130.826 | -1.06 | 0.3923 | |
| | | 605.896 | 2.20 | | |

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