

# Analysis of annual energy consumption of air conditioning systems, calculated on the basis of probabilistic-statistical climate model

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**Abstract.** The calculations of energy consumption of heat, water and electricity by air conditioning systems, which provide the outdoor air processing according to different schemes, can be made only on the basis of data on the frequency of combinations of the outdoor air temperature and its relative humidity. The probabilistic-statistical climate model has been chosen as the basis for the calculation results. On the basis of climatic models for Moscow, the outdoor air treatment in the air conditioning units, which operate according to the schemes of the direct flow with the first and second heating, as well as the adiabatic process in the humidifier unit in the cold period of the year and cooling in the surface air cooler in the warm period of the year with the subsequent second heating; with the first heating and the adiabatic process in the humidifier unit, equipped with an air bypass in the cold period of the year, as well as the controlled cooling process in the surface air cooler in the warm period of the year. As a result of the calculations it was found that all the components of energy costs are quite significant and cannot be neglected when comparing the options.

## 1. Introduction

Various economic comparisons require estimation of heat, water and electricity consumption by air conditioning systems during the year or separate parts of it [1-3].

The article considers the most popular air treatment schemes with the use of the appropriate central air conditioning systems (CACS) [4,5]:

- direct flow with the first and the second heating, as well as the adiabatic process in the humidifier unit in the cold period of the year and cooling in the surface air cooler in the warm period of the year with the subsequent second heating;
- with the first heating and the adiabatic process in the humidifier unit, equipped with an air bypassing loop (bypass) in the cold period of the year, and a controlled cooling process in the surface air cooler in the warm period of the year, then with a bypass. According to the results of the air humidification and the energy consumption this system is identical to CACS with the controlled air humidification process.

In the scheme with the second heating this second heating works all year round. When processing under the second heating scheme, the air is first subject to an adiabatic or polytropic cooling, and then it is heated by a second heating to the required supply air condition.



In the bypass scheme the desired supply air parameters are achieved by mixing the unprocessed part of the outdoor air with a part of the outdoor air, which has been humidified in the adiabatic humidification unit or chilled in the air cooler.

Thus, the scheme with the second heating is more energy consumptive, but it can accurately support the specified thermal and humid parameters of the indoor air in any situation.

The surface air cooler in these systems has been adopted as a halon one, that is, the evaporator of the separate refrigeration machine serves as the air cooler. The electric power in such CACS is spent on the drive of the main fan of the system, the pumps of the air heaters and the humidifier, on the drive of the compressor, the condenser cooling fans, as well as the operation of the automatic equipment. However, in some works [6-8] only the compressor drive consumptions are considered as the important ones and all other components are considered as minor ones.

The purpose of the article is to identify the annual energy consumption by the air conditioning units, which operate according to the above mentioned schemes, as well as to prove that the cost of the electricity for all of the above needs are significant and should be taken into account in any economic comparisons.

The climatic basis for the study was the probabilistic-statistical climate model for the city of Moscow [9,10]. In the applied version of the climate model, a grid of gradations in temperature with a step of 1 °C and the relative humidity of 2.5 % were adopted, as in [11] it had been proved that the doubling of the grid step in temperature and the relative humidity leads to a 40 % distortion of the cold production estimates, and, consequently, of the power consumption of the compressor and the condenser cooling fans.

## 2. Methods of investigations

The CACS energy consumption calculation for each combination of the temperature and the relative humidity of the outdoor air is based on the known thermodynamic air treatment formulas in the equipment units [12,13]. To determine the type of the outdoor air specific treatment at any given combination of parameters, the calculation should begin with the specification of the weather zone to which this combination belongs.

The area of possible combinations of the temperature and the relative humidity in the construction region is divided on the  $I-d$ -diagram into the weather zones, describing the boundaries between them depending on the adopted air treatment scheme in the CACS unit, as well as the specified conditions of the required thermal-humid state of the indoor air, the thermal-humid ratio of the supply air processing in the room. The divisions into the weather zones are known and published in the literature [14-17]. Within one weather zone, the system operates in the same mode. The CACS, which enable the outdoor air processing according to the considered schemes, operate in 7 weather zones.

The climate probabilistic-statistical model provides the repeatability of each combination of the temperature and the humidity within the cell with a temperature gradation of 1 °C and a relative humidity of 2.5 %. The parameters of the outdoor air, which are characterized by the center of each cell, enable the determination of the instantaneous heat, cold, electricity and water consumption.

## 3. Calculation results

The outdoor air flow rate has been adopted the same for all the units and made 10,000 kg/h. The CACSA support the optimal year conditions in the premises, i.e. the temperature from 19 °C to 24 °C, and the relative humidity from 30 % to 60 %. The calculations have been performed for the variants of the 5 °C operating temperature difference between the indoor and the supply air. The mode of operation of the units has been considered in two versions: from 9 hours to 18 hours and around the clock.

Table 1 shows the annual energy consumption of the CACS with a second heating during the unit operation within 24 hours and the working day from 9 to 18 hours with a heat-humidity ratio of the supply air treatment of 5,000 kJ/kg, 20,000 kJ/kg, 60,000 kJ/kg. In the column "Electrical power consumption by the refrigerating machine" the annual power consumption on the drive of the

compressor and the condenser cooling fans is specified. The number of the unit operation hours around the clock is 5928 hours per year, and from 9 to 18 hours – 2223 hours. The annual electricity consumption of the main fans of the systems is approximately the same and makes 21807.7 kW·h for 24 hour operation mode and 8180.6 kW·h for the operation mode from 9 am to 18 pm.

**Table 1.** Annual consumption of heat, cold, water and electricity at different values of heat and humidity ratio of changes in the state of the air in the room.

Heat to humidity ratio kJ/kg	Heat consumption of the first preheating air heater, $Q_{h1}$ , kW·h	Heat consumption of the second preheating air heater, $Q_{h2}$ , kW·h	Cold consumption, $Q_c$ , kW·h	Water consumption, $W$ , kg	Electricity consumption of the pump at the first/ the second preheating, $N_{h1}/N_{h2}$ , kW·h	Electricity consumption by the cooling machine, $N_c$ , kW·h	Electricity consumption of the humidifier, $N_{hum}$ , kW·h
Secondary preheating scheme, from 9 a.m. to 18 p.m.							
5000	47 523.6	237	29 288.1	15 126.7	76.8/192.7	13 472.5	44.3
20 000	107 308.1	194	17 101.1	29 313.2	140.3/190.7	7 866.5	69.5
60 000	118 711.6	186	15 764.9	32 089.6	149.6/190.1	7 251.9	72.8
Secondary preheating scheme, 24 hours							
5000	133 458.4	657	59 782.9	32 699.8	213.0/527.1	27 500.1	110.9
20 000	298 881.2	539	33 134.4	68 301.3	385.8/517.3	15 241.8	181.8
60 000	330 234.3	519	30 451.1	75 311.1	410.4/514.1	14 007.5	191.3
Bypass scheme, from 9 a.m. to 18 p.m.							
5000	222 787.5	no	21 045.0	9 432.6	279,5/no	9 680.7	57.1
20 000	241 516.9	no	9 514.7	23 371.2	262,6/no	4 736.8	91.4
60 000	246 303.0	no	8520.6	26 106.1	260,6/no	3 919.5	96.9
Bypass scheme, 24 hours							
5000	633 593.8	no	49 267.7	22 324.4	815,4/no	22 663.1	135.9
20 000	677 131.8	no	19 119.9	57 683.9	768,3/no	8 795.1	222.2
60 000	689 221.0	no	16 672.8	64 724.6	759,6/no	7 669.5	237.2

The fact that the pump of the humidifier in the bypass air treatment scheme consumes a little more electricity than in the second heating scheme, despite the fact that the supply air moisture requires less water, is explained by the longer operation of the pump in the bypass scheme.

Since the air flow rate in all compared cases remains constant, the changes in the power consumption of the pump and fan drive are little changed. The electrical power consumption of all CACS slightly increases with the rise in the required indoor temperature. The increase in the internal heat emissions resulting in the greater difference of the working temperatures, requires larger amounts of electricity when the room air thermal and humid treatment process is  $\varepsilon = 5000$  kJ/kg. The electricity consumption with bigger  $\Delta t$  if  $\varepsilon = 20\,000$  kJ/kg and  $\varepsilon = 60\,000$  kJ/kg is weakly expressed.

Contrary to a popular opinion that the greatest electricity consumption is required for the operation of refrigeration machines, the calculations show that the biggest year electricity consumption accounts for the main fan drive, and only after that to the cold generation. However, this conclusion is made for the systems that assimilate the room heat excesses, which do not exceed the consumption of cold for the outside air cooling up to the supply air condition. The power consumption for the cold production is calculated at the 2.5 cooling coefficient, which should be considered very low. And despite this, the power consumption turned to be not high. The electricity power for the production of cold in the warm period of the year is not consumed all the time when the fan is running. In addition, modern air-cooled refrigerating machines have an average cooling coefficient in the conditions of Moscow about

3.5-4.5. Therefore, the electricity consumption for the air conditioning is not the most expending item [18].

A comparison of the energy resource consumption by air conditioners operating according to the two presented schemes is given in the table 2.

**Table 2.** The ratio of the resource consumed by the air conditioner, which works according to the bypass scheme, to the one consumed by the air conditioner, which works according to the scheme with the second preheating.

Heat to humidity ratio kJ/kg	Heat		Water		Cold		Electrical power	
	from 9 a.m. to 18 p.m.	24 hours	from 9 a.m. to 18 p.m.	24 hours	from 9 a.m. to 18 p.m.	24 hours	from 9 a.m. to 18 p.m.	24 hours
5000	0.78	0.80	0.623	0.683	0.718	0.824	0.820	0.905
20 000	0.80	0.808	0.797	0.844	0.556	0.577	0.807	0.828
60 000	0.806	0.811	0.813	0.859	0.540	0.547	0.786	0.825

It should be noted that the ratios decrease slightly with increasing the range of the maintained room temperature.

With a constant heat and humidity ratio of the air treatment process, the relative need for heat for the supply air treatment increases with a decrease in the required difference in the operating temperature. That is, the heat relative need for the outside air heating is greater at smaller indoor heat emissions assimilated by the supply air with a smaller temperature difference. The CACS, working in the morning, evening and night hours longer, have a greater relative heat consumption too. The effect of the heat and humidity ratio of the air treatment process in the room is, that at small values of the heat and humidity ratio the need for heat for the supply air heating is less than at large ones [19, 20].

The cold consumption by different CACS occurs at 24 °C, which is the same indoor air design temperature for all of them, so the air temperature for the cold period of the year does not matter.

The ratio of bypass CACS power consumption to the consumption of CACS with the second heating is equalized due to the large power consumption values of the fan operating continuously during the whole shift. Moreover, the ratios increase with the bigger maintained temperature in the room, as well as with the increase in the working hours.

It is interesting to note that the probabilistic-statistical climate model enables determination of the consumption of individual energy resources and water in each weather zone. This is important because this study shows how the consumption of each resource is distributed throughout the year.

Table 3 shows such data for the second heating system.

#### 4. Conclusion

The quantitative assessment of heat, cold, electricity and water consumption is based on a detailed (with a fine breakdown by temperature and relative humidity) probabilistic-statistical model of the climate of Moscow, providing the repeatability of these combinations of the outdoor air parameters. It allowed us to show that all the components of the energy consumption are quite significant and they can not be neglected when comparing the options.

**Table 3.** Annual power consumptions of CACS with the second preheating in different weather zones.

Weather zone	Heat consumption of the first preheating air heater. $Q_{h1}$ . kW·h	Heat consumption of the second preheating air heater. $Q_{h2}$ . kW·h	Electricity consumption of the pump at the first preheating. $N_{h1}$ . kW·h	Electricity consumption of the pump at the second preheating. $N_{h2}$ . kW·h	Water consumption. $W$ . kg	Electricity consumption of the humidifier. $N_{hum}$ . kW·h	Cold consumption. $Q_c$ . kW·h	Electrical power consumed by the compressor. $N_c$ . kW·h	Number of operation hours in the weather zone. h
<b>CACS with second preheating (24 hours)</b>									
<b>Heat to humidity ratio 5 000 kJ/kg</b>									
1	133 449	269 196	125.2	125.2	18 015	90.3	-	-	1290.5
2	-	56 239	-	44.9	8 980	47.1	-	-	463.1
3	-	292 005	-	298.4	-	-	-	-	3075.9
4	-	-	-	-	-	-	-	-	491.8
5	-	18 609	-	27.1	5 705	19.5	17 888	7 155	279.0
6	-	21 673	-	31.5	-	-	41 802	16 663	324.9
7	10	28	0.4	0.4	-	-	93	37	0.4
<b>Heat to humidity ratio 20 000 kJ/kg</b>									
1	298 881	357 607	226.8	226.8	48 212	163.7	-	-	2338.1
2	-	36 500	-	59.6	14 801	43.0	-	-	614.6
3	-	123 471	-	188.7	-	-	-	-	1945.3
4	-	-	-	-	-	-	-	-	611.4
5	-	12 760	-	24.0	5 289	17.3	13 481	5 393	247.3
6	-	8 714	-	16.4	-	-	19 653	7 854	168.9
<b>Heat to humidity ratio 60 000 kJ/kg</b>									
1	330 234	362 690	241.2	241.2	54 275	174.1	-	-	2487.0
2	-	35 409	-	65.5	16 347	47.2	-	-	675.1
3	-	102 027	-	170.1	-	-	-	-	1753.7
4	-	-	-	-	-	-	-	-	625.6
5	-	11 321	-	22.2	4 690	16.1	13 066	5 227	229.3
6	-	7 654	-	15.0	-	-	17 385	6 949	155.0
<b>CACS with second preheating (9 a.m.18 p.m.)</b>									
<b>Heat to humidity ratio 5 000 kJ/kg</b>									
1	47 521	97 039	45.1	45.1	6 574	32.6	-	-	465.2
2	-	23 377	-	22.2	5141	24.4	-	-	228.4
3	-	97 866	-	97.8	-	-	-	-	1008.4
4	-	-	-	-	-	-	-	-	235.7
5	-	10 796	-	15.7	3 411	11.3	10 726	4 291	161.9
6	-	8 188	-	11.9	-	-	18 527	7 366	122.8
7	3	7	0.02	0.02	-	-	34	11	0.2
<b>Heat to humidity ratio 20 000 kJ/kg</b>									
1	107 308	130 019	82.5	82.5	17 732	59.5	-	-	850.1
2	-	15 510	-	31.2	8 473	27.7	-	-	321.9
3	-	38 410	-	56.7	-	-	-	-	584.5
4	-	-	-	-	-	-	-	-	262.3
5	-	7 137	-	13.4	3 108	9.7	7 984	3 194	138.3
6	-	3 370	-	6.3	-	-	9 117	3 639	65.3
<b>Heat to humidity ratio 60 000 kJ/kg</b>									
1	118 712	132 254	87.9	87.9	19 989	63.5	-	-	906.9
2	-	14 673	-	34.3	9 342	40.3	-	-	353.2
3	-	30 772	-	50.0	-	-	-	-	515.9
4	-	-	-	-	-	-	-	-	259.8
5	-	6 277	-	12.3	2 758	8.9	7 688	3 075	127.1
6	-	2 942	-	5.8	-	-	8 077	3 225	59.6

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