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ENERGY EFFICIENCY IN HVAC SYSTEM USING AIR COOLING BY DIRECT EVAPORATION

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Abstract: In developed countries, buildings represent between 30 and 40% of the total energy consumed and office buildings are one of the largest energy consumers. Specialty literature presents studies that showing air conditioning systems represent between 10 and 60% of total energy consumption in office buildings. This indicates that the heating / cooling system of a building has great potential for energy savings. The article presents classical cooling systems and describe the HVAC system used to cooling experimental room, located in a building from Timisoara. In order to determine the energy efficiency of the above-mentioned HVAC system, four control scenarios were made by varying the chilled water temperature at the evaporator exit and cooling mode of the chiller condenser. The indoor air temperature was set to the comfort value of 25°C, and the measurements were made within 8 hours for each scenario during July. Based on the analysis of the four proposed HVAC scenarios, it was concluded that the performance of a chiller may vary significantly depending on the system's partial loads and the evaporator and condenser operating temperatures, and For air-cooled chillers, the performance coefficient increases as the outside air temperature (te) decreases and the temperature of the cooled water (twr) increases at the evaporator outlet.
Keywords: Energy efficiency, HVAC system, air cooling, performance, comfort

INTRODUCTION

In present, the European energy efficiency target for 2020 adopted in 2007 is 20 as compared to 2005. For Romania, this indicative target is expressed as the level of savings of primary energy of 43 meters and 30.3 meters of final energy consumption respectively. The Commission's 2017 evaluation report shows that, despite Romania's situation in the group of 15 Member States that have achieved energy savings over the annual level needed to reach the target, the situation has deteriorated in the residential and transport sectors, which is the mitigation of the gap energy consumption compared to Western European countries.

For 2030, the European Energy Efficiency Target, commonly established for all Member States in 2014 was 27%. This percentage was raised to 32.5% in 2018, by the consensus between the European Commission, the European Parliament and the EU Council with a further upward revision clause until 2023. Such growth requires significant investment, supported by public policies and stimulated by favorable regulations [1-2].

Considering the current worldwide energy consumption requirements, the energy efficiency of heating and air-conditioning systems has an increasing share. So far, in most European countries, the energy required to heat the premises is higher than the energy used to cool the premises. In the future, the energy consumption for space cooling will increase due to increasing internal heat gains and the use of glazed facades. Low energy buildings are characterized by good thermal insulation and low heat losses between the interior and exterior, and high-quality glazed surfaces have U-value coefficients below 1.5 W/m^{2}K.

In developed countries, buildings represent between 30 and 40% of the total energy consumed. Office buildings are one of the largest energy consumers [3-4]. Generally, most of the energy is used to maintain an acceptable level of comfort inside buildings. Lighting and heating/cooling systems are the biggest consumers. Studies show that air conditioning systems represent between 10 and 60% of total energy consumption in office buildings [5]. This indicates that the heating / cooling system of a building has great potential for energy savings.

CONVENTIONAL AIR CONDITIONING SYSTEMS

Conventional air conditioning systems depend on the vapor compression cycle to ensure cooling. Types of conventional vapor compression systems are autonomous, factory-assembled compact units, separate compressor units and condensing units and internal air-flow units (CTAs) and cold systems. Cold systems use refrigerants to cool the water that is then distributed to CTA batteries. With each of these systems, cooled air is delivered via terminal devices to the space to be cooled.

— Experimental Parameters

When the liquid water evaporates and turns into water vapor, the heat entering the evaporation process is removed from the air, thus cooling the air temperature. Evaporative air conditioners are effective in medium to low-humidity climates and consume much less energy than other types of air conditioning systems. Air conditioners may have direct or indirect evaporation. In direct evaporation cooling, the water evaporates directly into the supply air stream, thereby lowering the temperature of the dry air thermometer when the humidity increases. Latent air heat is used to evaporate the air. Evaporation cools the air while increasing the moisture content or relative humidity. Do not add or remove heat from the air, so it is an adiabatic process.

Figure 1 shows a psychometric analysis of this direct evaporation cooling process. The air temperature entering the dry thermometer (T_{DB}) is 43.3°C, relative humidity, φ is 15%, and the thermodynamic temperature of the wet thermometer (T_{WB}) is 22.2°C. The cooling threshold of 21.1°C can be reached from 43.3°C to 22.2°C by adding only water to the supply air. In this case, the feed air stream was cooled down to 3.3°C of the thermodynamic limit of the wet thermometer, so it was 84% more efficient than the theoretically possible 17.8°C. Obtaining 90% to 95% of the wet thermometer temperature is often the target of direct cooling performance.

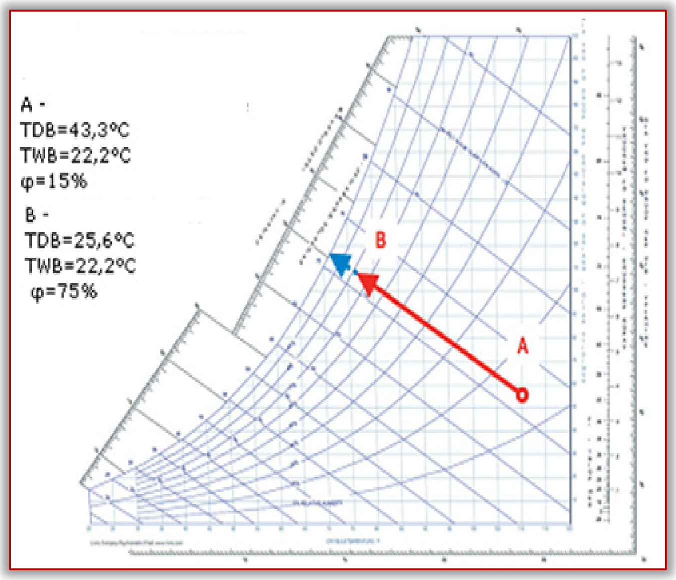

Figure 1. Direct evaporation cooling process presented psychometrically

A psychometric graph can show why direct evaporation cooling works well in dry climates and not very well in wet conditions. Using Figure 2, if we start with T_{DB} = 35°C (A) with 70% relative humidity, that air can only be cooled directly by 5°C before reaching saturation to T_{WB} = 30°C. Going further and to the left of the short red line to A, the final air temperature can be read by following the vertical lines to the temperature of the dry thermometer. Starting with T_{DB} = 35°C air (B) at relative humidity of 10%, that air can be cooled to 18.3°C before condensation, for 19.4°C when cooling. This is a significant increase in the amount of cooling that can be assured against wet air at the same temperature.

The cooling effect of direct evaporation air conditioners is the result of the amount of moisture added to the air. In very dry climates, direct cooling is quite efficient for cooling dry dry air. Additionally, moisture added to the air can be a bonus.

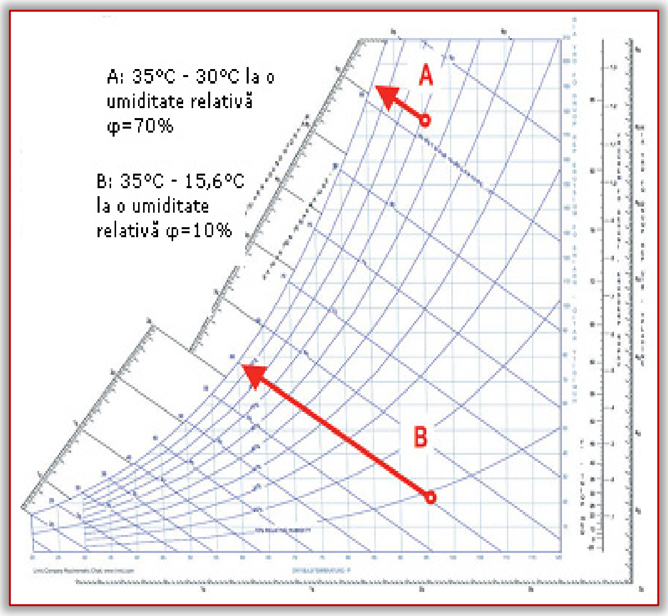

Figure 2. Comparison with direct evaporation cooling when starting with T_{DB} = 35°C at φ = 70% versus φ = 10%

PRESENTATION OF THE EXPERIMENTAL ROOM

The experimental room located in Timisoara (Figure 3) is bounded by an east-facing exterior wall, two adjacent interior walls of an office and an inner wall adjacent to a corridor, a floor separating the thermal area studied by a meeting room of a common floor with a top-level office.

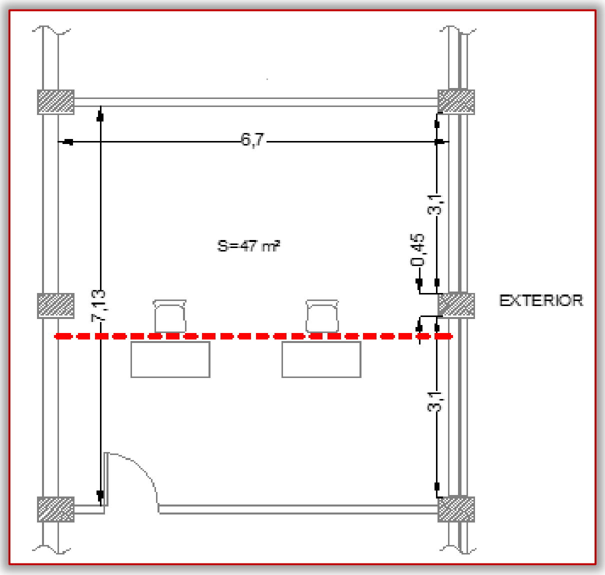

Figure 3. Plan of the experimental room

The calculations were made for Timişoara, with average daily air temperature in July, t_{em}=24.7°C, absolute air humidity, x_e=10.5 g/kg and the degree of system security ventilation/air conditioning of 90%.

The following basic data is also known:

- the height of the room is 3.70 m;
- total area of the room S = 47m^2, and the surface of the inner doors Su = 2.10 m^2;
- the glazed surface is 17 m^2 of thermopan glass, representing 64% of the exterior wall surface;
- the floor consists of parquet (0.02 m), screed (0.05 m), reinforced concrete slab (0.125 m), lime plaster (0.02 m);
- the floor consists of tiles (0.015 m), screed (0.05 m), reinforced concrete slab (0.125 m), lime plaster (0.02 m);
- the outer wall consists of lime plaster (0.02 m), autoclaved cellular concrete (0.25 m), cement mortar (0.03 m) and open brick (0.05 m);
- interior walls are made of lime plaster (0.004 m), gypsum board (0.02 m) and mineral wool (0,10 m);
- the occupants of the room are 2, each with a computer;
- electrical lighting has a thermal failure of 5 W/m^2;
- the tilt angle of the outer wall s = 90°C;
- azimuthal angle of the outer wall = -90°.

DESCRIPTION OF THE HVAC SYSTEM USED FOR AIR CONDITIONING

In order to achieve the comfort parameters in the experimental room, the following equipment was used:

- an air-cooled, air-cooled Daikin chiller (CH) (CH) with a refrigerant vapor compression (R410a) with a cooling capacity of 7.1 kW;
- a GEA air handling unit (CTA) with a maximum air flow rate of 2700 m^3/h, consisting of a mixing chamber, a fine F5 class filter, a flat-bottomed heating battery with fins and a collector- hot water dispenser, cooling fan and centrifugal fan with frequency converter and maximum pressure loss of 250 Pa;
- two wall-mounted ventilators (VCV), one Climaveneta type and one Rhoss type, with a total cooling output of 3.2 kW.

The thermal agent used in the ventilation / air conditioning systems analyzed is chilled water, using the chiller air-cooled. It has a cooling capacity of 7.1 kW under the condition that the outside air temperature is 35°C and the cooled water produced has a temperature of 7°C and the flow temperature difference between flow and return is Δt = 5°C.

The chiller was chosen taking into account the variation in EER energy efficiency with outdoor air temperature.

Heat pumps operating in heating mode are characterized by the COP defined by the relationship (1) [6-7]:

$$COP = \frac{Q_c}{P_e} \qquad (1)$$

in which:

Q_c is the heating power in kW;

P_e - electric power to drive the heat pump, in kW.

The performance coefficient of a chiller or heat pump in cooling mode is obtained with relationship (2) [6-7]:

$$COP = \frac{EER}{3{,}413} \qquad (2)$$

in which 3.413 is the transformation factor of Watt in Btu / h.

It has to be taken into account that the performance of such a refrigeration system can vary significantly [6-7]. Performance depends on partial system loads and evaporator and condenser operating temperatures.

In Europe, the energy efficiency rating for cooling for chiller operation at partial loads is called the EER_{sez}, defined by the relationship (3) [6-7]:

$$EER_{sez} = \frac{1 \cdot EER_{100\%} + 42 \cdot EER_{75\%} + 45 \cdot EER_{50\%} + 12 \cdot EER_{25\%}}{100} \qquad (3)$$

where: $EER_{100\%}$, $EER_{75\%}$, $EER_{50\%}$, and $EER_{25\%}$ are yields of the cold water generator operating at various partial loads (respectively 100%, 75%, 50% and 25%) calculated for the outdoor air temperatures listed in Table 1 for the evaporator water outlet temperature of 6°C or 7°C and for the 5°C cold water temperature range.

Table 1. External air temperatures for different partial cooling loads

Cooling load	100%	75%	50%	25%
Outdoor air temperature	35°C	30°C	25°C	20°C

Applying relations (1) and (2) EER values were calculated at maximum load and using the relation (3) the values of the EER seasonal energy efficiency ratio were determined depending on the chiller's efficiency operating at different partial loads. The values obtained for EER and EERsez are summarized in Table 2. It is noted that the chiller selected for unfavorable conditions (te = 35°C, twr = 7°C and Δt = 5°C) has a seasonal energy efficiency ratio EERsez = 10.57.

Table 2. Chiller energy efficiency

t_{wr} [°C]	t_e [°C]				EER
	20	25	30	35	
	EER				
7	12.72	11.02	9.53	8.21	
11	13.76	11.90	10.25	8.70	
13	14.26	12.33	10.63	9.12	
16	15.01	12.97	11.20	9.86	
20	16.04	13.85	11.94	10.91	

Operation of the chiller is done by means of a Daikin ARC448A2 wall control, which, depending on the set DHW temperature, gives the compressor control. The chilled water temperature can be set between 5°C and 22°C. When the chilled water temperature has reached the set value, the compressor stops running, leaving only the circulating pump and the cooling fans of the condenser in the chiller.

The condenser cooling system on the chiller can be changed by placing a water spray equipment in the condenser area. The outdoor air temperature decreases to the wet bulb temperature, a process performed at constant enthalpy.

Condensers cooled only with air or water only make the condensation heat from the refrigerant only by the sensitive heat of the coolant causing significant air or water flows [8]. At the same time, heating this cooling agent leads to a higher condensing temperature.

Improvements to these two inconveniences can be achieved by using mixed cooled condensers with water and air. The water takes over the condensing heat from the refrigerant and vaporizes partially. Through this vaporization and heat exchange between water and air, the water flowing over the surface of the condenser maintains virtually the constant temperature and can be recirculated and used again in the cooling process [9].

In this way, a low condensing temperature is maintained, only 2-3°C higher than the water temperature, and lower water and air flow rates are required.

As the cooling system is based on water evaporation and the takeover of these vapors by the air, the hygrometric state of the air is of great importance to the operation of the condenser. This will be more effective when the air will have a lower relative humidity.

RESULTS OF EXPERIMENTAL RESEARCH

In order to determine the energy efficiency of the above-mentioned HVAC system, four control scenarios were made by varying the chilled water temperature at the evaporator exit and cooling mode of the chiller condenser shown in Table 3.

Table 3. Scenarios systems

Scenario	Type of cooling the condenser	Chilled water temperature twr [°C]
1	air	5
2	air-water	5
3	air	8
4	air-water	8

The indoor air temperature was set to the comfort value of 25°C, and the measurements were made within 8 hours for each scenario during July.

In scenarios 2 and 4, a mixed (air-water) cooling of the chiller condenser was carried out by spraying the water by means of three jets mounted at a distance of 0.2 m from the chiller housing (Fig.4). This results in a fog curtain that lowers the outside air temperature in the area to the humidity of the thermometer by cooling it iztalpically [10].

Figure 4. Water spray system for condenser cooling

To determine the distance of the dowel locations, the temperature and humidity of the outdoor air were measured before and after water spraying through the three wells.

The values recorded before spraying were 28°C for air temperature and 60% for relative humidity. After spraying, the values listed in Table 4 were recorded, corresponding to the different spacing of the nozzle. As the strongest cooling of the outside air, up to 22.2°C, was obtained at a distance of 0.2 m, the dowels were mounted at this distance from the chiller housing.

Table 4. Distance between the nozzles

Distance between the nozzle [m]	Relative humidity of outdoor air after water spraying [%]
0.40	83
0.35	87
0.30	91
0.20	98

In all scenarios shown above, the electrical energy consumption of each equipment of the system analyzed, indoor and outdoor air temperatures and the intensity of global solar radiation were measured.

Table 5 shows the measured power consumption values for the HVAC system and each considered control scenario.

Table 5. E_{el} power consumption values, in kWh, for the HVAC system in the four scenarios

Scenario	Chiller	CTA	VCV	Total
1	7.58	8.67	0.37	16.62
2	5.78	8.67	0.62	15.07
3	7.74	8.67	0.66	17.07
4	5.66	8.67	0.71	15.04

The fresh air from the treatment plant has a temperature equal to that set for indoor air, 25°C.

Analyzing the four scenarios for the HVAC system, the most efficient energy scenario is scenario 4 where the electricity consumed is 15.04 kWh. The share of electricity consumed by the chiller is only 37.6% due to the high electrical consumption registered at CTA (Figure 5). VCV electricity consumption is less than 5% of the total power consumption of the system.

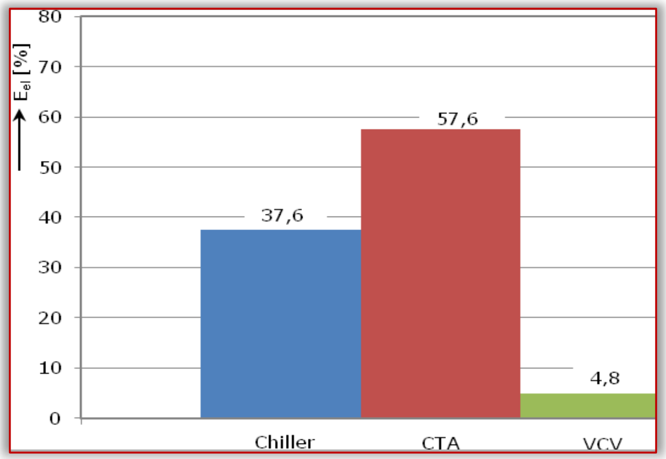

Figure 5. The share of electricity consumption of HVAC system equipment

Considering the share of electrical power consumption on equipment to reduce the power consumption of the system, it is necessary to act simultaneously to improve the energy efficiency of the chiller and to reduce the specific power of the CTA fans.

To determine the influence of chiller cooling mode on electricity consumption, scenarios 1 to 2 and 3 to 4 were compared for HVAC. Table 6 shows the E_{el} power consumption for two scenarios of the HVAC system, resulting in the corresponding ΔEel energy savings.

Table 6 The influence of chiller cooling mode on electricity consumption

System		Scenario 1	2	3	4
HVAC	Eel [kWh]	16.62	15.07	17.07	15.04
	ΔEel [%]	9.32		11.89	

It is noted that the HVAC system records a ΔE_{el} electricity saving when using the air-water chiller (scenarios 2 and 4).

Spraying water causes the average outside air temperature to drop so that refrigerant condensation occurs much faster.

Table 7. Changing outdoor air temperature following water spraying

Te[°C] before	Te[°C] after
22.36	21.08
23.48	21.2
24.17	21.66
25.08	21.96
28.31	24.21
28.35	24.17
31.12	24.81
33.22	26.22

For the HVAC system, the highest energy saving of 11.89% is obtained when the chilled water temperature is 8°C.

Therefore, it is recommended to use the HVAC system with an air-cooled chiller and a chilled water temperature of 8°C. The energy efficiency of this system was determined by measuring the E_{rac} cooling energy and total E_{el} consumed energy, depending on the outside air temperature, and is shown in Table 8.

Table 8. Energy efficiency of the HVAC system

Nr. crt.	te [°C]	Erac [kWh]	Eel [kWh]	COPsist	EERsist
1	26.76	1.13	0.89	1.27	4.34
2	28.25	1.07	0.88	1.21	4.13
3	30.34	1.34	0.98	1.37	4.68
4	31.91	1.18	0.95	1.24	4.24
5	33.09	1.00	0.87	1.14	3.90

It is noted that at an increase of about 7°C of outdoor air temperature from 26.76°C to 33.09°C, EER_{sist} is reduced by 10.13% from 4.34 to 3.90.

CONCLUSIONS

Depending on the solution adopted, ventilation / air conditioning systems are made up of different components, such as chiller (CH), air conditioning (CTA), cooling tower, fan coil (VCV).

The performance of a chiller may vary significantly depending on the system's partial loads and the evaporator and condenser operating temperatures. Chillers with staggered partial loads operate at maximum load only a few days per year / season, taking into account the seasonal or annual performance coefficient (COP_{sez} (an))

For air-cooled chillers, the performance coefficient increases as the outside air temperature (te) decreases and the temperature of the cooled water (twr) increases at the evaporator outlet.

The seasonal energy efficiency of the chilled water chiller equal to 19.9 is 28% higher than that of the air cooled chiller with a piston compressor equal to 14.3 and 35% Air cooled chiller efficiency with screw compressor equal to 12.9.

Cooling chillers only with air or only with water make the condensation heat transfer from the refrigerant only through the sensible heat of the coolant, leading to significant air or water flows. One solution to alleviate this inconvenience is the mixed air / air cooling of the capacitors.

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