U.P.B. Sci. Bull., Series C, Vol. 82, Iss. 3, 2020 ISSN 2286-3540

EXPERIMENTAL FOULING ANALYSIS IN HVAC ROOFTOP UNITS

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The purpose of the article is to highlight the impact of filters and heat exchangers under fouled operating conditions that intensify over time, during a seasonal operation for air conditioning systems. It is highlighted the optimal interval in which the preventive maintenance should take place. This experimental analysis, it is based on the operation under fouled conditions of a rooftop unit with mechanical vapor compression (DX unit). Results show that the operation in fouled conditions could reduce air flow through the evaporator by 20%, energy efficiency ratio EER up to 40% and electrical power consumption of the entire HVAC system increases by 14% or even more.

Keywords: air flow, filters, fouling, HVAC, maintenance

1. Introduction

There are few publications which have demonstrated that more than half of installed air conditioning systems have significant defects, and an improper maintenance of them can increase their energy use up to 50% [1].
An inadequate program of maintenance applied at the refrigeration / heating systems leads to low parameters of the air flow, which have influences in supply air temperature in the conditioned space. At the same time, operating costs increase, and the reliability of the system will become vulnerable [2].

Future trend concerning the art of HVAC maintenance program will continue to improve more accurate techniques for evaluating refrigerant charge and other diagnostic methods.

This article presents the operating of the HVAC systems under clean and fouled conditions, the scope being to illustrate the importance of maintaining a proper maintenance. It is an experimental study, which analyzes the variation of the parameters (air flow rate, thermodynamic refrigeration cycle and power consumption) under clean and fouled conditions of supply air filters and heat exchanger coil - condenser.

Concerning the fouling effect in HVAC systems, experimental studies have been carried out over time according to the references [7]-[12].

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Table 1

Fouling effects – results from various HVAC studies

N^0	NAME OF CAUSE	THE RESULT OF THE STUDY
1	The influence of filters fouling	Increased electrical consumptions with 10-70%
2	Lack of management	Inefficiency of maintenance activities
3	Fouled filters	Increased pressure drop on their surface with 20%
		The fan power consumption increases with 9.5%
4	Inadequate technical inspections and tests	Defects occurring in over 30% of total operational failures
5	Microbiological fouling of 10%, at a speed of the secondary thermal agent (air) of 2m/s	The heat transfer coefficient is reduced by 7.2%. The pressure drop increases by 21.8%.
6	Air flow restriction through evaporator with 25%	Reduction of refrigeration power and COP by 12%.
7	Surface of condenser fouling with 50%	Increased electric consumption of compressors by 23% Increased supply air temperature by 4.5ºC
8	Accuracy of data collection	Efficiency of planning and implementation of maintenance activities

As a result of consequences, the paper highlights the importance of optimum preventive maintenance cycle in order to reduce failures number and maintenance costs.

2. Maintenance costs – theoretical point of view

In order to determine the optimum preventive/corrective maintenance intervention time in site, various publications present a mathematical formula, which describes the costs and risks. It is assumed that if one component presents a failure before time *t*, a corrective action ought to occur. If the device doesn't have a failure before time *t*, a preventive action must take place. Actually, the broken component must be replaced after a failure or after a period of operation *t*, it doesn't matter which takes place first [3], [5].

Fig.1 shows that the cost of failures per unit time get become lower as preventive maintenance occurs more often, but in the same time the cost of preventive maintenance increases.

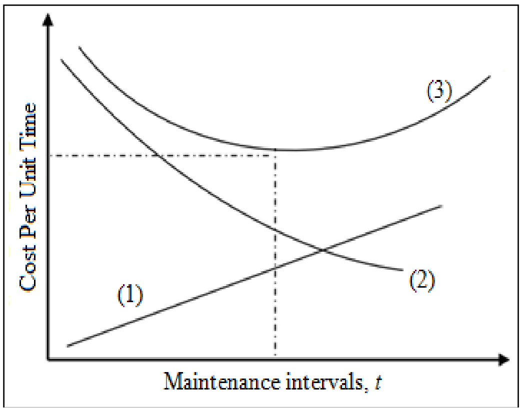


Fig. 1. Optimum schedule for preventive maintenance [4]
(1) Failure (Corrective maintenance costs)
(2) Preventive maintenance costs
(3) Total (Minimum cost of replacement)

In this regard, there is a minimum intersection point of total cost of failures and preventive maintenance per unit time, which means the optimum schedule for preventive maintenance. Some scientific sources illustrated that the optimum maintenance intervention time is considered by decreasing the total cost per unit time [6]:

$$CPUT(t) = \frac{C_p R(t) + C_u[1 - R(t)]}{\int_0^t R(s)ds} \quad (1)$$

where:
$CPUT$ - cost per unit time
C_p - cost of planned (preventive replacement)
C_u - cost of unplanned (corrective replacement)
$R(t)$ - reliability function for the component at time t
t - preventive maintenance time
$R(s)$ - expected cycle length

Practically, as it is deduced in this article, optimum intervention time can be found more easier at a point of intersection at which maintenance costs (MC) are almost the same with operational costs (OC).
Based on the determination of the operational costs of the system, the following expressions were used in determining the technical parameters and efficiency:

- Compression mechanical work:

$$l_c = h_2 - h_1 \quad [kJ/kg] \tag{2}$$

- Enthalpy of the refrigerant at the exit of the compressor:

$$h_2 = f(T_c, p_c) \quad [kJ/kg] \tag{3}$$

- Enthalpy of the refrigerant at the inlet of the compressor:

$$h_1 = f(T_v, p_v) \quad [kJ/kg] \tag{4}$$

- Refrigeration efficiency (Energy Efficiency Ratio, EER):

$$\varepsilon_f = \frac{q'_0}{l_c} \quad [-] \tag{5}$$

$$q'_0 = \Delta q_{0,cu} + q_0 + \Delta q_{0,oh} \quad [kJ/kg] \tag{6}$$

Where:
h_1 - Enthalpy of the refrigerant at the inlet of the compressor;
h_2 - Enthalpy of the refrigerant at the exit of the compressor;
T_v and T_c – evaporation and condensation temperature;
p_v and p_c - evaporation and condensation pressure;
q'_0 - specific refrigeration capacity;
$\Delta q_{0,cu}$ – subcooling degree of the refrigerant at the outlet of the condenser
$\Delta q_{0,oh}$ – overheating (superheat) degree of the refrigerant at the compressor suction;

3. Methodology and Assumptions

Fouled conditions refer to the operating conditions of the installation, where the filters and heat exchangers (evaporator and condenser) have dust deposits on their surface. The filters used are of 2 types: G4 (coarse filtration) and F9 (fine filtration).

To calculate the optimum maintenance intervention time in site, the following considerations have been taken into account:

- Upstream evaporator filters (efficiency G4 + F9) are considered 100% being fouled after 6 months of operating time;
- Preventive maintenance cost per rooftop unit;
- Decrease in thermodinamic paramters;
- Operational costs (electrical power consumption);

The existing air filters which are installed in the analyzed rooftop unit, could be classified by taking into account their minimum efficiency report value (MERV), into five categories: low, medium, high, and ultrahigh efficiency of particles retentions and pressure drop [13]:

- Filters with class of filtration G4 – represents group of filters used for coarse dust particles from 5 to 80 μm (average efficiency of retention > 90%);
- Filters with class of filtration F9 – represents group of filters used for fine dusts particles from 1 to 3 μm (average efficiency of retention > 95%).

4. Experimental case study

The aim of this experimental article highlights the importance of maintaining clean filters and heat exchangers coils in a HVAC system compared with operation under fouled conditions. The experimental study was performed in cooling mode, during 6 months upon an air conditioning rooftop unit type with mechanical vapor compression, which serves the climate in an area from a shopping center located in Brasov (Romania). Various parameters of the installation were analyzed and measured. Some of the technical specifications concerning the experimental HVAC system are presented in table below:

Table 2

Technical specifications of the HVAC system

Rated air flow	27500 m^3/h
Cooling capacity	140.2 kW
Heating capacity	148 kW
Refrigerant type	R 410 A

Measurements of parameters and data collection were performed comparatively with clean and fouled filters. Thermodynamics parameters of the refrigeration cycle and air flow were analyzed monthly over the period of 6 months, the values being recorded for one hour at each measurement stage.

The parameters registered with the manifold Testo 550 are: compressor suction and discharge pressures, vaporization and condensation temperatures, temperature at the inlet of the compressor, temperature at the outlet of the condenser, subcooling and superheat temperatures. Air parameters have been measured with an anemometer.

Regarding fouling effects, Fig.2 illustrates the state of the condenser coil under fouled conditions, almost half of the coil surface is covered with dust particles. On the other side, at the internal heat exchanger coil (evaporator) of the rooftop unit, supply air filters get dirty from month to month. Normally, in clean condition of filters, pressure drop ranges between 250-270 Pa. As a consequence of advanced filter fouling, pressure drop reaches the high limit of 500 Pa.

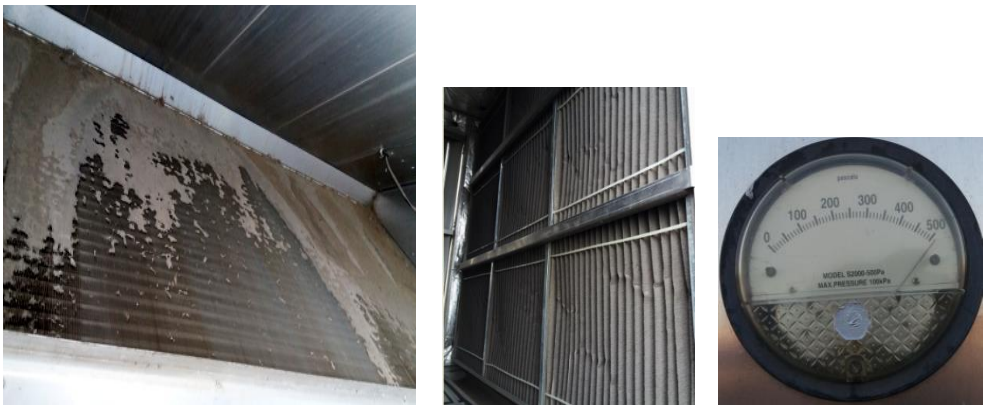


Fig. 2 Condenser coil and filters under fouled conditions

5. Results

Both types of supply air filters are installed upstream of the evaporator coil in order to protect it by reducing its fouling and improve indoor air quality in the conditioned space.

Fig.3 shows that in 6 months of filters operating time in summer conditions, decreasing air flow takes place as the particles level cover the filters surface.

The influence over time of the dust deposits on to the filters surface has a polynomial characteristic, the increase of the pressure drop on the filters from 260 Pa (when the filters are clean), to 500 Pa, it means a reduction of the air flow when passing through the vaporizer by 20%. Under these conditions, the cooling capacity of the evaporator is reduced by 33%. As the degree of fouling increases, the value of the square root of the polynomial equation tends to decrease.

Continuing the operation of the HVAC system under fouled conditions of filters that will have pronounced decrease of the air flow when passing through the evaporator coil, leads to the increase of the polynomial degree, which will be translated by amplifying the slope of the line.

Similar effects are presented graphically in figure 6 for the condenser coil operation under fouling conditions.

The influence over time of the dust deposits on the condenser coil has a polynomial characteristic, the effect of the fouling means a decrease of the air flow by 16%. Under these summer conditions, condenser heating capacity is reduced by 26%. As the air flow through the evaporator is reduced by 20% (equivalent of 4530 m^3/h), due to the clogging of the filters, the heat transfer to the secondary thermal agent is also influenced. Thus, the supply air temperature (the air flow entering the conditioned space) at the exit of the evaporator increases by 19%, this means 4ºC.

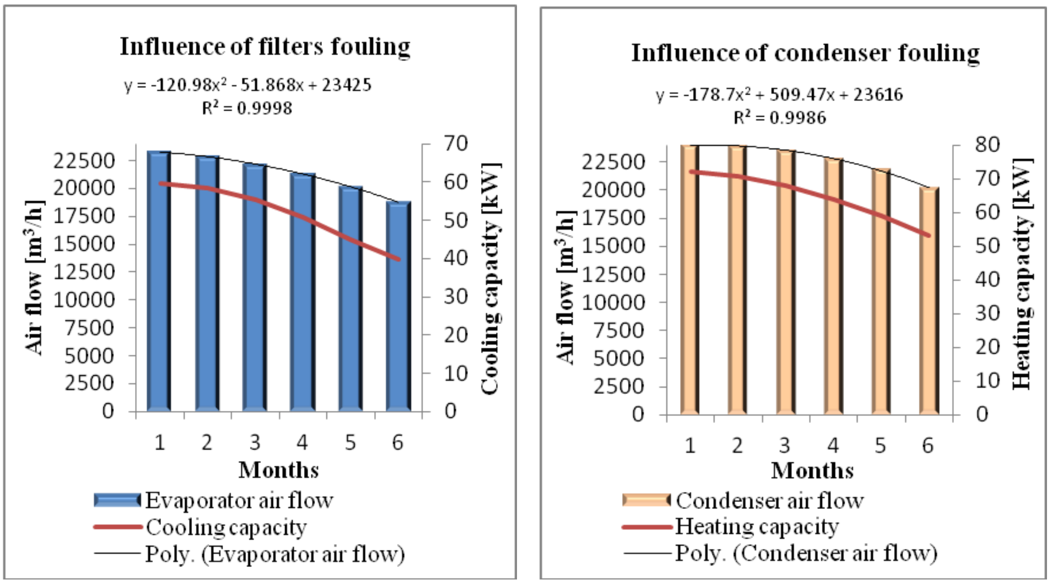


Fig. 3 Restriction of air flow to the evaporator and condenser during the analyzed period

When the air flow is restricted to the passage through the filter surface and through the condenser, situation caused by fouling effect, make thermodynamic parameters from refrigerant cycle to be affected. Most of these effects are:

- Increase of condenser pressure with 28% (9.6 ºC);
- Higher condensing temperature, with 14 ºC;
- Low values of subcooling and superheat (more than 40%), caused by improper heat transfer between refrigerant and air flow passing the coils;
- Simultaneously with the increase of the compressors mechanical work (by 22%) the specific thermal capacities are reduced by 19.5% at the evaporator and 11% at the condenser.
- Long-term fouling effects tend to reduce the energy efficiency ratio EER up to 40% (from 4.7 to 2.9 regarding this study).

Refrigerant measurements and data collection were carried out over the 6 months. Some recorded examples are given in Fig.4, from clean (on the left) to fouled conditions (on the right).

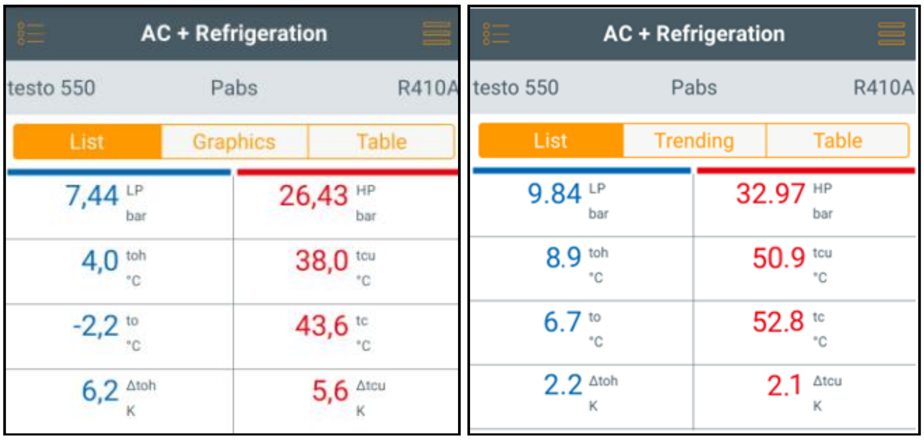
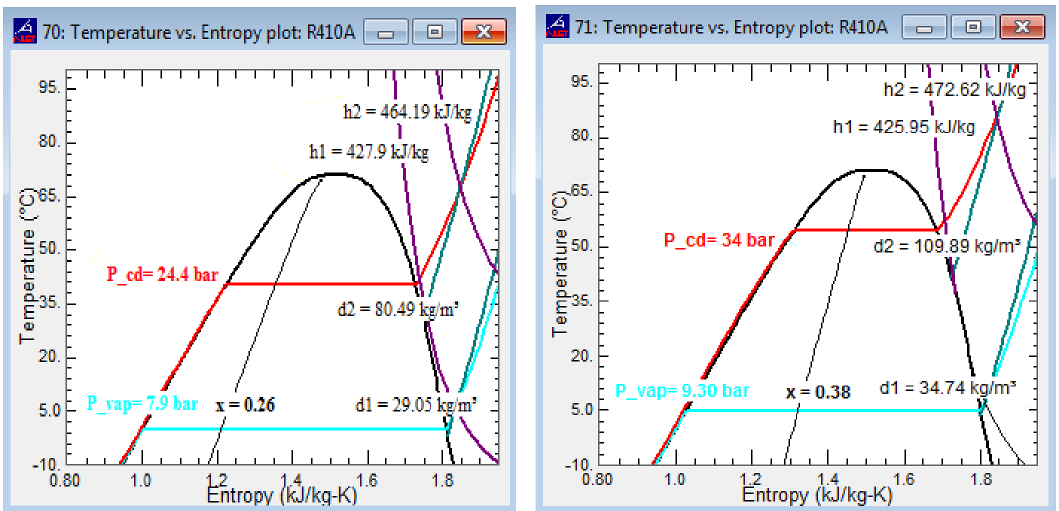


Fig. 4 Refrigerant cycle data recorded in clean and fouled conditions

LP- low pressure [bar]; HP- high pressure [bar]; toh –compressor suction temperature [ºC]
tcu –condenser outlet temperature [ºC]; to – evaporation temperature [ºC]
tc – condensation temperature [ºC]; Δtoh – superheat [K]; Δtcu – subcooling [K]

For a better view of the pressures, enthalpies, densities, and refrigerant quality, graphical representations for both operating conditions are illustrated in Fig. 5.



a) clean conditions of operation **b)** fouled conditions of operation

Fig. 5 Plot in clean and fouled conditions for Temperature - Entropy diagram

P_cd; P_vap – condensing pressure; evaporator pressure [bar]; h1; h2 – enthalpy of the refrigerant at the inlet and outlet of the compressor [kJ/kg]; d1; d2 – vapor density at the inlet and outlet of the compressor [kg/m^3]; x – vapor quality

Also it could be observed higher compression ratios when the HVAC system operates in fouled conditions. Vapor quality increases from 0.26 in clean conditions, to 0.38 in fouled conditions, which means the decrease of the specific refrigeration power.
In order o have clear view concerning the refrigerant cycle operation during 6 months, Fig.6 shows lg*(p)-h* diagram, which presents simultaneously 3 stages:

- **Green frame** represents operating in clean conditions
- **Blue frame** represents the operating time when the compressor internal efficiency gets below 70% and its isentropic efficiency become lower than 90%. This means that filter changing time should take place. For this case study, it corresponds to the period of operation at the end of the 3rd month;
- **Red frame** represents the operating cycle after 6 months (under fouled conditions of filters and condenser coil), where the specific refrigeration power is diminished by 19.5%.

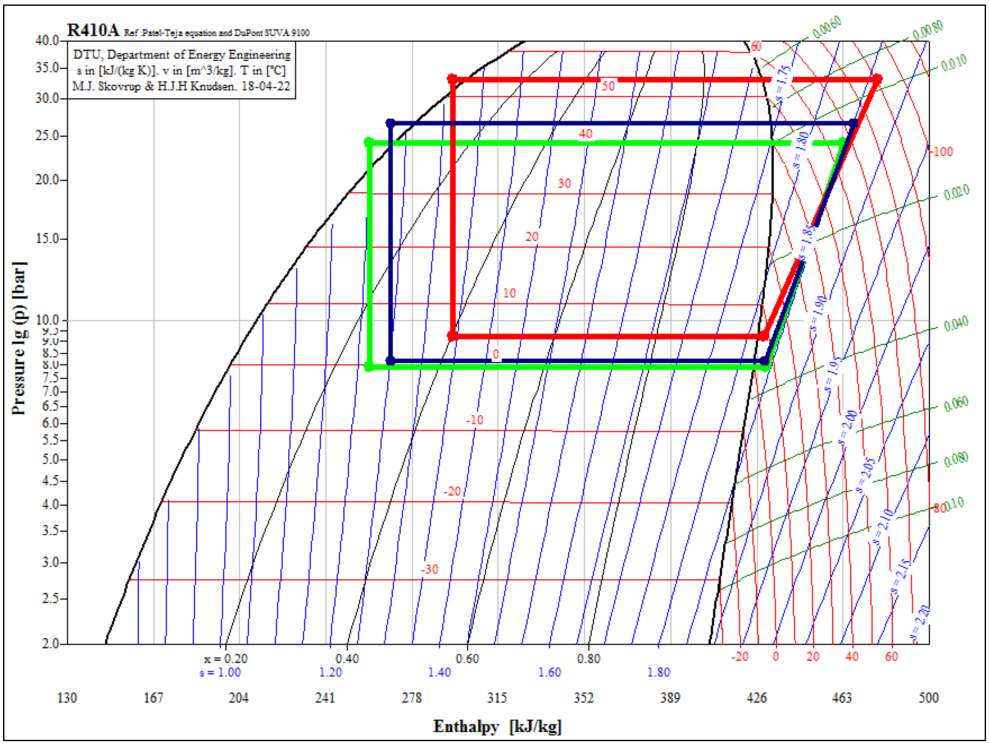


Fig. 6 Comparative representation of refrigeration cycles in diagram lg *(p)-h*

As expected, fouling effect has a higher power consumption impact for supply air filters than operating in normal clean conditions. Thus, Table 3 shows the electricity power consumption and the costs for each analyzed month. It is noted that the highest electricity consumption during cooling mode operation is recorded in the 6th month (August). The increase in power consumption (by 14%) is given by extended operating time of fans and compressors, caused by the phenomenon of high level fouled filters and condenser, but also to the increase of the outside temperature, which influence heat transfer at the condenser side.

Table 3

Centralized table with Thermodynamic parameters and Costs for a HVAC rooftop unit

Mth.	Evap. Pressure [bar]	Cond. Pressure [bar]	Mech. Work [kJ/kg]	EER [-]	Power Consumpt. [kW]	MC €	OC €	TC €
1	7.90	24.40	36.31	4.7	45.04	1262.0	356.0	1618.0
2	8.00	25.15	36.31	4.6	46.15	631.0	387.0	1018.0
3	8.15	26.90	37.69	4.3	47.03	421.0	423.0	844.0
4	8.50	29.00	40.04	3.9	47.88	315.0	501.0	816.0
5	9.00	32.36	44.54	3.2	50.57	252.0	667.0	919.0
6	9.30	34.00	46.67	2.9	50.92	210.0	853.0	1063.0

In Fig.7 costs are graphically represented, the intersection point of the two curves representing the optimum time for maintenance intervention in site.

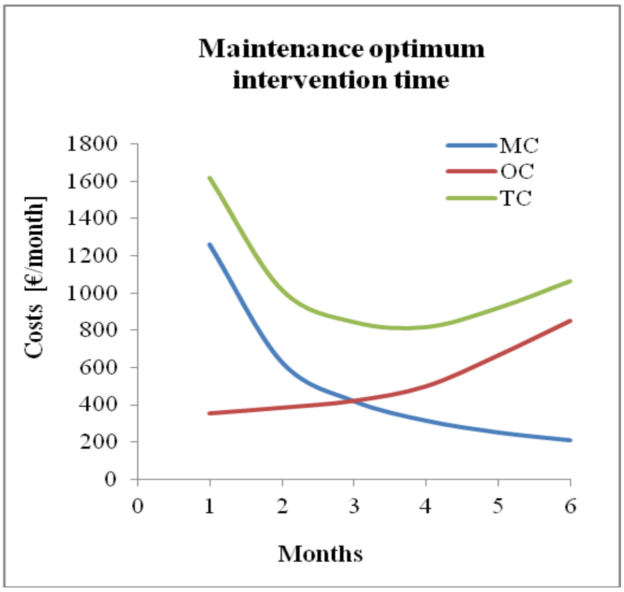


Fig. 7 Optimum intervention time

MC – maintenance costs; **OC** – operational costs; **TC** – total costs

In order to analyze from an economic point of view the optimum time of maintenance, which involves cleaning/replacing the filters and cleaning the condenser coil, technical maintenance, and analysis was carried out, where the maintenance costs and the operating costs were divided monthly (for 6 months).

6. Conclusions

Filters are the critical components in this system, because when they become fouled at a high level, they cannot guarantee the indoor air quality and thermal comfort in conditioned space. As the filters become dirty, their efficiency decreases and electrical consumption increases. A typical fixed time interval for filters changing or cleaning may not be optimum, because it depends on the external and internal conditions of operation. Thermodynamic parameters must also be taken into account. Preventive maintenance activity has long-term benefits, improves system reliability, reduces cost of replacements and minimize system downtime. This article demonstrates that inadequate maintenance program, which doesn't have an optimum intervention time, causes negative impact such as: high operational and maintenance costs, low air flow, increased electrical power consumption and low efficiency. Air particles act as an obstacle and create a bad convection heat transfer.

During 6 months of operation in summer conditions, air filters and condenser coil become dirty and as a result causes the following effects:

- Long time the dust deposit on the filters and condenser coil has a polynomial characteristic.
- Supply air flow through the evaporator coil decreases with 20%, and filters pressure drop increases from 260 Pa to 500 Pa.
- Also vapor quality increases from 0.26 to 0.38 and as a consequence, evaporator cooling capacity is reduced by 33%.
- Air flow passing through the condenser coil is reduced by 16%, this means a condenser heating capacity reduced by 26%. Hence, supply air temperature increases by 19%.
- Energy efficiency ratio EER, decrease from 4.7 to 2.9

From a technical point of view, the effects of filter and condenser fouling significantly influence the parameters from the 4th month of operation, which shows that maintenance intervals which are required for corrective interventions should take place every 3 months.

From the economic point of view, the monthly operating expenses (electricity consumption) and the monthly frequency with the maintenance were analyzed. It was found that in the first two months of operation, the maintenance costs are higher than the operating costs, and at the end of 3 months of operation, the maintenance costs are almost the same with operating costs. After that, operating costs increase due to the electric consumption of fans and compressors. Thus, the optimum maintenance frequency is 3 at months.

Regarding these, maintenance operations during summer conditions, should mean:

- After first 3 months
  - Visual inspection;
  - Cleaning or replacing filters;
- After 6 months (3 months from first visit)
  - Visual inspection;
  - Cleaning or replacing filters;
  - Cleaning of the heat exchanger coils;
  - Technical maintenance: which consists in thermodynamics parameters measurements, air flow measurements, electrical intensities of fans and compressors, etc.

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