POLITEHNICA UNIVERSITY OF BUCHAREST
FACULTY OF POWER ENGINEERING

DOCTORAL THESIS ABSTRACT

Influence in fouling operation on the efficiency of HVAC systems

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CONTENTS

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INTRODUCTION

At present, at the same time as air quality is deteriorating due to pollution, air conditioning has become a key requirement.

The air conditioning process has a wide spread and a continuous technological development of equipment, known by the abbreviation of HVAC (Heating Ventilation and Air Conditioning). Air conditioning involves treating the air in indoor environments (office buildings, homes, commercial spaces, industrial halls), creating and maintaining a climate in certain conditions of temperature, humidity and air circulation, so that it produces the desired effects on the occupants of the spaces. conditioned, or precise climate applications for deposits [1].

IMPORTANCE AND CURRENTNESS OF THE SUBJECT:

In order to maintain the desired thermal comfort in conditioned spaces, air conditioning systems must operate at optimal efficiency parameters. The long-term operation of this equipment without taking into account an efficient management plan in the maintenance activity, leads to a decrease in the efficiency and reliability of the air conditioning system, at the same time as the increase of operating costs and the number of subsequent corrective interventions.

This results in errors and malfunctions that significantly increase the operating costs and the costs of corrective interventions (those of repair or replacement of defective parts).

ORIGINAL CONTRIBUTIONS:

The main original contributions from the study were:

- Analysis in the study of a long operating time (two seasons of six months each), in cooling and heating regimes, so the real research conditions, significant for HVAC type installations;;
- Analysis of the monthly influence that the fouling effect has on the electrical and thermodynamic parameters of the system, for each operating season;
- Determining the optimal intervention time for the maintenance activity, based on a technical-economic analysis;
- Hierarchy of technical parameters that influence the operation in fouling conditions;
- Highlighting the importance of the optimal maintenance operation for the efficient operation of HVAC installations;
- Proposing the types of maintenance actions required to be performed to ensure the efficient operation of HVAC installations;

1. CURRENT STATE OF SCIENTIFIC RESEARCH

1.1 Technical aspects

In order to maintain the desired indoor thermal comfort, energy must be extracted or introduced into the space where the air conditioning takes place. Thus, the energy in the form of sensible heat or latent heat must be supplied in the cold season and extracted in the warm season, from the conditioned space.

Fouling of heat exchangers and filters is a common phenomenon and with a particularly important impact in terms of its influence on the efficiency and reliability of HVAC installations. Neglecting this phenomenon leads to a decrease in cooling / heating efficiency and an increase in electricity consumption [5]. The sequence of stages of the fouling phenomenon on the filters or on the heat exchange surfaces of the heat exchangers takes place as follows: the initial deposition phase, the surface transport, the deposition on the respective surface, part of the deposits is removed with the passage of the secondary thermal agent flow (air flow), the aging of the particulate deposits [4].

1.2 Management aspects

The current trend when it comes to investing in new HVAC equipment is to consider not only the cost of purchasing it, but the total cost of the equipment.

A survey of different brands shows that 70% of the total cost of air conditioning equipment is represented by energy consumption. In order for this consumption to be maintained in optimal parameters, the technical staff and the management of the sector for which the implementation of the HVAC solution is desired, must know very well the energy performances of the equipment.

Current European regulations place a lot of emphasis on equipment certifications, such as ErP (Energy related Products) 2018 or even ErP 2021.

The approach to the subject of maintenance is proactive or reactive. Proactive maintenance eliminates problems before they occur. John E. Day, Jr. (1993) did an excellent job developing the concept of proactive maintenance [64] .

1.3 Published articles

As a starting point in the scientific research of the thesis, was the article "Aspects regarding fouling of the heat exchanger coils and filters on the performance of packaged air to air HVAC system", held at the IEEE conference (ICES), Bucharest, 2017 [69].

After a period of operation of 1 year in operation of the HVAC system of rooftop type analyzed, without intervention with maintenance, were analyzed under the same conditions (in the hot season), four cases of operation of the installation with filters and heat exchangers in clean conditions, respectively fouling conditions.

The results of the study showed the following aspects:

- Filters fouling has a much greater impact on electricity consumption than fouling of heat exchangers. Thus, compared to the maximum efficiency conditions (clean operating conditions), fouling of heat exchangers generates an 8% higher electricity consumption, while fouling of air filters generates a 19% higher electricity consumption.
- Filters fouling decreases the refrigeration efficiency of the system by 7% more than fouling of the heat exchangers.
- Simultaneous fouling of filters and heat exchangers reduces the refrigeration efficiency by up to 22%, and the supply air temperature in the conditioned space increases by 6ºC.

The previous article is reinforced by another study: "Experimental fouling analysis in HVAC rooftop units", article published in 2020 in the UPB Scientific Bulletin [70], which highlights the importance of timely maintenance and avoid the operation of the system in fouled conditions.

The research is based on an analysis period of six months, during the operation of the installation in the hot season. During operation, the influences of fouling of filters and heat exchangers on the technical parameters of the installation are analyzed on a monthly basis.

The article shows the importance of management in the maintenance activity, so that it is done correctly and optimally. For this, not only the expenses with the frequency of maintenance interventions must be taken into account, but also the operating expenses (mostly given by the consumption of electricity).

The two articles described above represent the starting points and realization of the thesis.

2. TECHNICAL DESCRIPTION OF THE ANALYZED HVAC SYSTEM

The analyzed installation is a reversible, double-flow air-to-air HVAC system, coupled to a condensing thermal module. The field of applicability for this type of systems is intended for commercial spaces (shopping galleries, restaurant area), where the emphasis is not only on the introduction, but also on the extraction of air.

The analyzed HVAC system is a reversible heat pump, its operating regimes being:

- air conditioning (with thermodynamics);
- free-cooling;
- heat pump + condensing boilers;
- condensing boilers.

3. FOULING EFFECTS AND CASE STUDY DESCRIPTION

This chapter presents the aspects related to the effects that may occur as a result of the simultaneous fouling of the filters and the condenser, during the operation of the installation for a period of six months in the hot season and six months in the cold season. The analyzed HVAC plant is located outside, on to the rooftop of a shopping center, the fouling phenomenon is strongly influenced by dust deposits that come from both the recirculation of air from the conditioned space, but also from the external environment with the intake of fresh air, air that is loaded with dust particles and that comes from the developing urban neighborhood.

3. 1 Case study description

In this paper, the analysis of the refrigeration cycle is performed in conditions of maximum efficiency (clean operating conditions) and fouled conditions.

Therefore, for six months, the influence of filter and condenser fouling on the parameters of the HVAC installation was analyzed simultaneously, both during the operation in the hot season and during the operation in the cold season.

The parameters of the refrigeration cycle were analyzed monthly over a period of six months, the values being recorded for one hour at each stage of measurements.

The parameters recorded with the Testo 550 are: compressor inlet and discharge pressures, vaporization and condensation temperatures, compressor inlet temperature, condenser outlet temperature, degree of overheating, degree of subcooling.

4. CALCULATION OF THE REFRIGERATION CYCLE OF THE EXPERIMENTAL INSTALLATION

This chapter presents the description of the installation from a theoretical point of view in the *Ig-p* and *T-s* thermodynamic diagrams. Also, the relations for the calculation of the efficiency of the installation, in both operating regimes, on the thermodynamic measurements performed are presented.

5. RESULTS OF CALCULATIONS AND ANALYSIS OF OPERATING REGIMES

5.1 **Tables with measurements and results of calculations**

This subchapter presents the centralization of the average values of the measured and calculated parameters, when operating in cooling and heating mode, both for the secondary thermal agent (air) and for the primary thermal agent (type R410A refrigerant).

The measured and calculated values for the six months were recorded at the end of each month corresponding to the analyzed season. The maximum efficiency parameters are recorded in the first month of operation; whether they are at the beginning or the end of it, the differences are insignificant. The influences on the parameters start to be visible from the second month of operation.

Comparing the operation of the installation in the hot season with its operation in the cold season, the effects of fouling that cause the restriction of air flow through filters and heat exchangers, are much more pronounced in the operation of the installation in the hot season.

Thus, the following aspects were found:

- After 6 months of operating in cooling mode:
  - fouling filters influences the decrease of the evaporator air flow by 20%;
  - evaporator cooling capacity decreases by 33%;
  - condenser heating capacity decreases by 26%;
  - supply air temperature into the conditioned space increases by 24% compared to the optimal value of 15.5ºC;
- After 6 months of operating in heating mode:
  - fouling filters influences the decrease of the condenser air flow by 16%;
  - evaporator cooling capacity decreases by 28%;
  - condenser heating capacity decreases by 20%;
  - supply air temperature into the conditioned space decreases by 7% compared to the optimal value of 33ºC;

5.2 **Representation and graphical analysis of the results**

Vaporization and condensation pressures have a fairly close evolution of the parameters in the first three months of operation, in both operating modes, the differences begin to be visible from the fourth month of operation, as the degree of filters and condenser fouling increases. Under advanced fouling conditions, the pressure values increase, especially for the condensing pressure during operation in the hot season, and the variation trends become unstable for the pressure values recorded in the last month of operation; the graphical evolution is no longer constant, it shows fluctuations.

Graphical representations of condensing pressure show that it is influenced to increase greatly during operation in the hot season. The reason could be attributed to three factors: the fouling of the filters in the way of the evaporator, the fouling of the condenser, the heat exchange of the condenser with the external environment at a much higher temperature in the hot season, compared to the operation in the cold season.

According to the graphic representations, at the condenser level the following aspects are noticed:

- The intensification of the fouling phenomenon during operation in the hot season, causes the condenser cooling by the heat exchange with the external environment to be affected due to the restriction of the air flow when passing through the pipe bundles. At the same time, the high temperature of the external environment makes it difficult to release calories, therefore, after a period of operation of six months, the condensing temperature increases by 34%, and the temperature at the exit of the condenser increases by 47%.
- The intensification of the fouling phenomenon when operating in the cold season is less intense in terms of influence of rising temperatures. The condensing temperature increases by 15%, while the temperature at the outlet of the condenser increases by 30%.

As the air flow when passing through the evaporator is reduced by 20% (equivalent to 4530 m^3/h for the analyzed case), due to the clogging of the filters, the heat transfer to the secondary thermal agent is also influenced. Thus, the temperature of the secondary thermal agent (the air introduced into the conditioned space) at the exit of the evaporator increases by 23.6%.

When operating in the cold season, the fouling of the filters decreases the air flow when passing through the condenser by 16%, therefore, the temperature of the air flow introduced into the air conditioner is reduced by 7.5%.

Vapor quality at the evaporator inlet for clean conditions is 0.25 to 0.26, while the vapor quality for analysis in fouled conditions shifts to the right at 0.38.

Moving the quality vapor to the right at the evaporator inlet indicates a decrease in specific cooling and heating capacity.

- In summer, the specific refrigerating power is reduced from 171 kJ/kg to 138 kJ/kg, and specific heating capacity is reduced from 207 kJ/kg to 185 kJ/kg.
- In winter, the specific refrigerating power is reduced from 173 kJ/kg to 149 kJ/kg, and specific heating capacity is reduced from 210 kJ/kg to 201 kJ/kg.

6. ECONOMIC ANALYSIS

The purpose of this chapter is to highlight the planning of maintenance interventions not only in terms of technical but also economic aspects.
For this stage, the costs were analyzed, which can be separated into two categories:

- *Operating costs*, which are represented by the electrical power consumption;
- *Maintenance costs,* which are mainly represented by the activities that involve purchase and replacement of filters, travel costs, etc .;

After these aspects are achieved, the optimal time for carrying out the preventive maintenance intervention is identified.

6.1 Analysis of electricity consumption

The main electrical consumers of the system are compressors and fans for supply and exhaust air. Electricity consumption and electricity costs are highlighted, when operating in both seasons, for each month analyzed.
Fouling filters and heat exchangers has the following effects:

- restricted air flow and inefficiency heat transfer;
- increasing the compressors mechanical work, which influences the increase of the consumed electric power;
- increase the consumed electric power of the air intake and extraction fans;

The effects listed above occur in both modes of operation. They intensify on a monthly basis and only prolong the operating time of the air conditioning system, while increasing operating costs, which increase exponentially as the efficiency of the installation decreases..

6.2 Maintenance cost analysis

According to the conclusions that take into account the technical aspects presented, the optimal intervention period for replacing / cleaning the filters is every 3 months. If we refer to the seasonal analysis of 6 months, and this intervention would be performed only once, the maintenance cost of this type would be minimal. But from a technical point of view the system would suffer.

At the same time, maintenance plans more often than 3 months, to prevent operation in fouling conditions are technically efficient for the installation, but are inefficient in terms of costs generated.

The optimal time of corrective intervention for cleaning depends on how intense the fouling process takes place. In some cases regular interventions can be scheduled (twice a year or once a year), other times the interventions need to be performed more frequently, which depends on the operating conditions of the entire HVAC system.

6.3 Optimal intervention time for maintenance

The long-term operation of air conditioning systems, without taking into account an adequate management plan in the maintenance activity, leads to a decrease in their efficiency and reliability, at the same time as the increase of operating costs and the number of subsequent corrective interventions.

Thus, in order to analyze from the economic point of view the optimal intervention time for the maintenance that supposes the operation in clean conditions of the HVAC system, the maintenance costs and the operating costs were analyzed monthly. Therefore, the costs are represented graphically, the point of intersection of the two curves representing the optimal time to do the maintenance.

7. MAINTENANCE EFFICIENCY MEASURES

The deviation of the parameters (from optimal conditions) was analyzed at 3 and 6 months because:

- The results presented in the previous chapters of this paper showed that from a technical-economic point of view, the optimal intervention for the operation of the air conditioning system in conditions of maximum efficiency, it is necessary to be carried out at the end of the third month of operation;
- Practices have shown that air conditioning systems operate for six months each season (cold / hot), and it is often common for maintenance work involving cleaning / replacing filters to be carried out every six months. Cleaning of heat exchangers is often neglected even after this period.

The main technical and economic indicators, easy to monitor / verify, which must involve the intervention of the maintenance team to proceed the corrective actions (cleaning / replacement of filters and cleaning of heat exchangers) are:

- ❖ **Technical indicators**
  - <u>Fiters pressure drop</u>
  - <u>Supply air temperature</u>
- ❖ **Economic indicators:**
  - <u>Increasing operating costs</u>

8. CONCLUSIONS

Reversible rooftop air conditioning unit described in this paper is analyzed in cooling mode (April-September) and heating mode (October-March) during six months of operation in each season. The thermodynamic parameters of the installation were analyzed simultaneously with the fouling of the filters and heat exchangers over time.

Simultaneous restriction of air flow through the evaporator and condenser, caused by the fouling phenomenon, has the following effects:

Whenever there is a reduced flow of air on the surface of the evaporator, its specific cooling power is diminished. As a consequence, the refrigerant does not vaporize completely, an effect that indicates a very low degree of overheating of the refrigerant at the entrance to the compressor. Even if the suction pressure and evaporator temperatures are low, the mass flow of refrigerant is also decreased.

If the condenser cannot remove calories to the outside environment, the pressure in it will increase. Once its heat exchange surface becomes dirty, the heat dissipation capacity decreases. Because the heat extracted by the process of vaporization, suction, released by the compressor motor and that resulting from compression is transmitted to the condenser, the heat exchange surface of the condenser must be kept clean, with the appropriate amount of air flow to ensure heat exchange. Otherwise, the system will operate at a discharge temperature and high condensing pressure and cause unwanted inefficiencies resulting from high compression ratios.

When the system operates at high condensing pressure, with undesirable inefficiencies, the suction pressure will tend to increase. Higher than normal suction pressure is caused by the mass flow of small refrigerant, which in turn is affected by the decrease in volumetric efficiency, resulting from the high condensing pressure.

For the analyzed installation, located outside, where there is a nearby area in full urban development that involves large amounts of dust released into the atmosphere, the measurements recorded and the calculations performed for the two operating regimes, indicate that:

- **From a technical point of view**, the effects of filters and condenser fouling significantly influence the parameters from the 4th month of operation, which shows that at 3 months of operation maintenance activity is required to replace/clean the filters and check/clean the condenser.
- **From an economic point of view**, it was found that in the first 2 months of operation, maintenance costs are high compared to operating costs, at 3 months of operation maintenance costs are slightly lower (about 3 ÷ 5%) compared to operating costs, where the latter increase due to the electricity consumption recorded by fans and compressors.

9. RESEARCH PERSPECTIVES

This doctoral thesis is a supplement to various studies conducted in the field by various authors, concerning the influences of the phenomenon of fouling on HVAC installations.

The study refers to a rooftop unit that serves the indoor climate in a commercial space. The subject of the thesis is a practical one, will represent interest in the future, and can be considered by maintenance techniciens for all similar equipments in operation. The technical analysis and graphical representations, as well as the preventive maintenance activities can be further developed in order to simulate the operation and maintenance of such HVAC systems.

The research directions can be used to improve the different components of such installations:

- From a constructive point of view, the internal air treatment compartments, especially the section where the heat exchanger and the filters are located, should be waterproofed and provided with drain holes on the outside, so that during the maintenance it allows cleaning with water jet and degreasing for the entire compartment, without the risk of leaks inside the piping network.
- Implementation of a centralized controller in the rooftop (not just in an interface in the conditioned space), to allow locally testing / verification / adjustment of all parameters during maintenance interventions. The HVAC rooftop unit type analyzed in this thesis has a such controller in the technical compartment, but there are similar equipment that does not have this controller, which makes technical maintenance operations difficult;
- There are currently alarms / warning signals for fouled filters. Most of the time they are neglected by maintenance operators. I believe that these alarms needs to be supplemented by information about increase in electricity consumption and the decrease in cooling and heating capacity. Thus, the maintenance operator would be much better informed about the diminished performance of the system when operating in fouled conditions.

Also, the following aspects can be added to the research perspectives:

- Analysis of different categories of pollutants on HVAC performance;
- HVAC performance analysis for various locations (regions, height levels, etc.);
- Introduction of artificial intelligence elements in monitoring the operation of HVAC systems with the possibility of automatic cleaning.

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