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# Experimental study of the solid fouling effect on the air-cooled apparatus characteristics

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Original article

## Abstract

External fouling on the heat exchange surface of air-cooled apparatus are formed during operation, which leads to a significant increase in energy consumption and deviations from the optimal operating mode of the entire system. This phenomenon is a problem for all energy conversion systems. This paper presents the experimental study results of a complex of a commercial cooled object with real fouling on the air condenser surface. To study the effect of fouling, an experimental bench was developed – a single-stage refrigerating machine that provides cold supply to a thermostatic chamber. Three types of fouling were used: sand, fluff and dust. Fouling were picked from the operating condensers and identical in the type of heat exchange surface to the experimental sample. With a change in the quantitative and qualitative composition of the fouling, the air condenser thermal and aerodynamic characteristics and the energy efficiency of the machine as a whole were determined. The experiment showed that at maximum fouling of the heat exchange surface with sand and fluff, air movement stops. This means that at a certain thickness of sand and fluff layer, an air impermeable dense structure is formed. Dust with the same form of filling the free space for the flow remains permeable to air. Experiments showed that the qualitative composition of the fouling is the main factor that determines the heat exchanger performance. It was found that from the experimental set of fouling, roadside dust has the greatest negative effect on the condenser characteristics and the machine as a whole. The aerodynamic properties of the heat exchanger depend to some extent on the qualitative composition of the fouling. As a conclusion, it was suggested that the process nature of air flow passing through the investigated fouling can be described as gas flows in porous media.

## Keywords

- air condenser
- fouling
- experimental bench
- heat exchange surface

## Authors contributions

A – Conceptualization
B – Methodology
C – Formal analysis
D – Software
E – Investigation
F – Data duration
G – Visualization
H – Writing – original draft preperation
I – Writing, reviewing & editing
J – Project administration
K – Funding acquisition

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None declared.

# Introduction

The analysis of the processes occurring in elements of the energy conversion systems should be based on a clear understanding of the criteria by which the element's operation will be evaluated in real conditions. These criteria are not difficult to formulate, but the task may be more difficult in some cases.

In the design process, researchers are faced with a choice problem. Choosing one option, they must discard the rest. The need to refuse, as a rule, is associated with the limited resources that are at the disposal of the project executors. These include: scientific calculation methods of various types, reference materials (own experimental data and data from other researchers, international energy and environmental requirements, etc.).

It is at the stage of project development the uncertainty factor often arises, which subsequently leads to additional energy and economic costs. With limited resources, the project still has to guarantee, with reasonable probability, efficient and reliable operation.

Heat exchangers of various types and purposes are the main elements of energy conversion systems. Fouling on the heat exchange surface that occur during operation are the main unresolved design problem. Such a physical phenomenon leads to a significant decrease in the overall intensity of the heat transfer process, a decrease in the apparatus heat load, an increase of coolants and heat carriers mass flow rate, and a temperature difference. The result is additional energy costs for production, in which the energy conversion machine is an element of the technological process.

Calcined solid fouling on the heat exchange surface of water-cooled apparatus, dust, paint, oil and rust on the heat exchange surface of air-cooled apparatus are the main sources of external solid fouling. Thermophysical properties changing in the heat and vapor insulation of pipelines, frost fouling on the heat exchange surface of low-temperature apparatus are additional fouling sources in refrigeration technique. This is an incomplete list of typical fouling that occur during the operation of low temperature systems. Obviously, the change in equipment operating characteristics over time must be factored into the project.

Investigations into the regularities of the fouling formation, from a practical point of view, are the basis in the information development and diagnostic systems for monitoring the heat exchangers efficiency, which in turn perform the functions of monitoring the quality of the entire system.

Timely diagnostics of the efficiency of the heat exchangers operation provides a condition for maintaining uninterrupted and long-term operation of all energy conversion systems equipment.

The fouling problem on the heat transfer surfaces of heat exchangers is not new. The thermal-hydraulic characteristics of heat exchangers are improved through the introduction of various innovative methods, such as: increasing the apparatus surface, intensifying the heat flows movement, etc [1–4]. However, until now there is no universal theory for predicting the fouling growth, the provisions of which could be used at the design stage.

All experimental and theoretical studies concern special cases of the fouling formation in heat transfer local conditions.

The scientific interest of the authors is the operating conditions of air-cooled heat exchangers in connection with the intensive development of commercial cold.

Papers [5, 6] are devoted to the study of window air conditioners, which are located in the coastal areas hotels. The fouling phenomena in evaporators and condensers were investigated. As a result, it was determined that the dominant fouling in the evaporator is mechanical particles, and in the condenser – corrosion, which is associated with the presence of salt particles in the ambient air.

In article [7], an experimental study of the real fouling effect in room air conditioners was carried out. The biological composition of the fouling material is presented. The results indicate a decrease in the energy efficiency of the room air conditioner.

In [8], plate and microchannel heat exchangers were investigated in various operating conditions: with a clean surface and fouling in the form of two different types of dust. Studies showed the influence of the geometric shape and size of the heat exchange surface on the character of fouling.

In [9], the characteristics of nine air condensers taken out of service at the end of their service life were investigated. After testing in a deposition state, the heat exchange surfaces were cleaned and experiments were carried out again. As a result, it was found that the uniformity of the fouling effect on heat transfer is absent, and the aerodynamic characteristics improve after cleaning the surface. The authors are of the opinion that it is necessary to revise the terms of maintenance of such condenser designs.

Paper [10] is a continuation of the previous research. The authors continue to argue that the fouling presence has almost no effect on the system energy efficiency, and in some cases, it can even improve the system performance. In the same work, the cleaning process of the heat exchange surface is described: with clean water and with the addition of detergents. It was found that detergents do not have a positive effect on subsequent heat transfer and aerodynamics. In some cases, washing with detergents impairs the heat transfer efficiency.

In [11], presents a method for creating a synthetic substance that simulates real fouling. The authors propose to use the obtained substance for simulating the fouling processes on the air condenser outer surface of split-system air conditioners. As a tests result, the fouling rate and it effect on heat transfer were determined.

In [12], the method of synthetic fouling described in [11] is used to study the frost fouling process on a clean and fouled surface of a low-temperature microchannel heat exchanger of a heat pump. The research result is the assertion that solid fouling accelerates the hoarfrost formation.

In [13], experimental studies of an air condenser with lamellar fins were carried out. Dust removed from the condensers surface of similar designs and operating conditions was used as solid fouling. The experiment results showed that with a gradual entrainment of the fouling layer, the following is observed: deterioration of heat transfer and aerodynamics, then stabilization of these processes, and then deterioration occurs again. According to the study results, it was hypothesized that the fouling represent a porous media.

All the works considered are a valuable contribution to the formation of engineering calculation methods that will make it possible to propose criteria for assessing the fouling effect on the operating characteristics of an energy conversion system.

Based on a review of research materials given in the technical literature, further experimental studies of thermal and aerodynamic processes in air condensers in the fouling presence become relevant.

The aim of this paper is to obtain experimental data for the air condenser with the different types of fouling for subsequent simulation of real physical processes in the condenser. To achieve this aim, the following tasks were solved:

- an experimental bench was designed;
- the condenser with real solid fouling in the form of dust, sand, fluff was tested;
- the experimental results were analyzed.

# Experimental bench

Constructive computational complexes were used to conduct the experiments:

- a bench with a uniform description of the model each element;
- a bench control system, which has a wide range of tools for completing the bench with control and measuring instrumentation and materials; with a formulation the program and the scope of the experiment, processing the experimental results, correcting them in the study course. The bench technological scheme represents a single-stage commercial refrigerating machine (Figure 1). The bench consists of two blocks: low-temperature [thermostatic chamber (1)] and high-temperature [climatic chamber (2)]. The thermostatic chamber contains: an air cooler (3), a thermostatic expansion valve (4) and an electric heater (5) with mechanical power control.

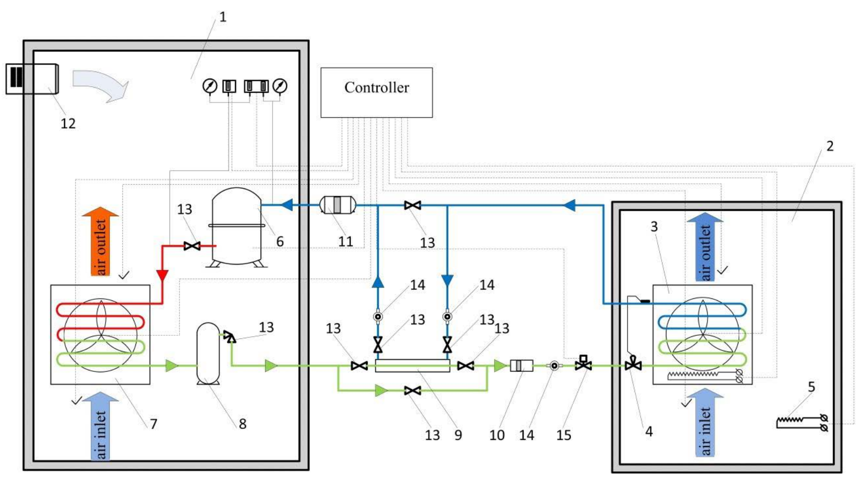



**Figure 1.** Concept scheme of the experimental bench

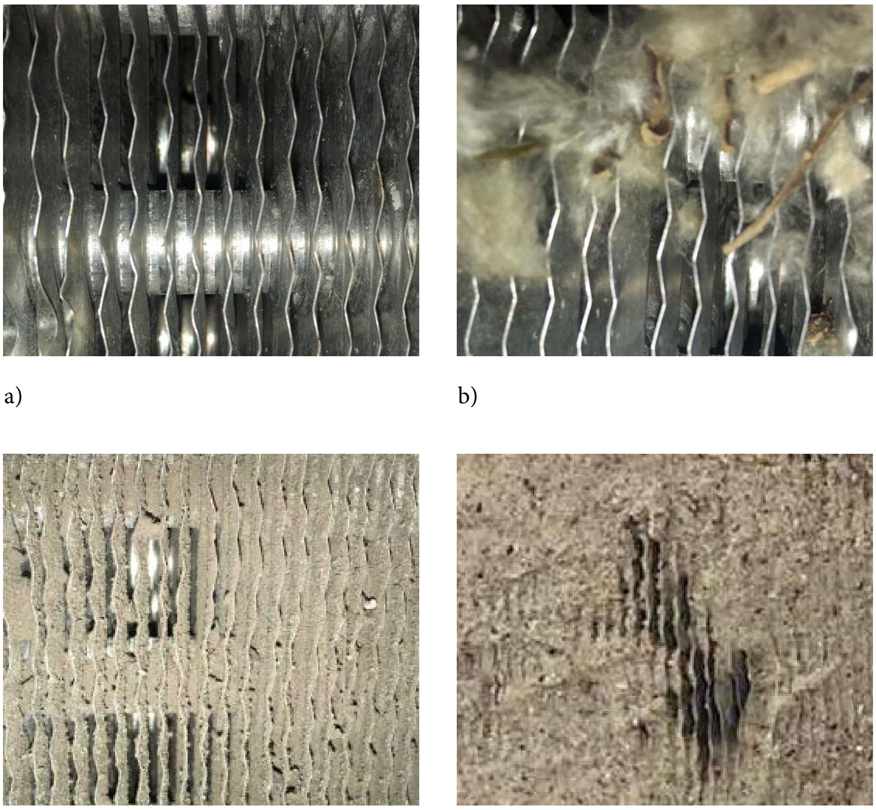
Where: 1 – thermostatic chamber; 2 – climatic chamber; 3 – air cooler; 4 – thermostatic expansion valve; 5 – electric heater; 6 – compressor; 7 – air condenser; 8 – receiver; 9 – regenerative heat exchanger; 10 – filter drain; 11 – mechanical cleaning filter; 12 – heat pump; 13 – shut-off valves; 14 – sight glasses; 15 – solenoid valve

The climatic chamber contains: a compressor (6), an air condenser (7), a receiver (8). The regenerative heat exchanger (9), filter drain (10) and mechanical cleaning filter (11) are placed outside the climatic chamber. The environmental conditions in the climatic chamber are simulated by a heat pump (12).
The refrigerant is R507 (50% of CHF2CF3 / 50% of CH3CF3).

The bench is equipped with control and measuring instrumentation, which is controlled by a common controller. Temperatures of air and refrigerant are measured using a thermometer with an external sensor UDS-12M-TK1 with an accuracy class of 0.1°C. The location of the temperature sensors is shown in Figure 1. The air flow velocity at the inlet to the condenser is measured with a portable digital anemometer with an accuracy of 0.01 m/s. Voltage and amperage are measured with standard AM-10A-VOX-RED ammeters and a PZEM-004 voltmeter with an accuracy class of 0.01 A and 1 V respectively. The pressure at the suction and discharge of the compressor are recorded by the low and high pressure gauges. The condenser is installed in a case providing equalization of the air flow at the input to the heat exchanger. Air circulation is provided by two axial fans. Dimensional specifications of the condenser are 290 x 580 x 120 mm. The heat exchange surface is made in the form of a criss-cross bundle of copper pipes with aluminum plate fins and a spacing of 30 x 30 mm. The fins have a thickness of 0.3 mm and a spacing of 3 mm.

## Program and research methodology

To study the operation characteristics of the condenser and the whole machine in real operating conditions, three types of fouling were used: dust, fluff and sand, which are taken from working condensers and identical to the experimental sample. Dust is taken from condensers installed on streets near the carriageway (roadside dust). The fluff is taken during the period of intense flowering of bushes and trees. This type fouling are typical in the regions of Eastern Europe. The beach sand is taken from resort areas of tourist sites, as sandstorms are big problems in the Middle East. The tests were carried out step by step.



a) b) c) d)

**Figure 2.** The heat exchange surface of the condenser during the experiment: a) clean surface; b) maximum fluff filling 45 g; c) maximum dust filling 850 g; d) maximum sand filling 2300 g

Step I. The machine operation with a clean condenser surface and constant temperature conditions in a thermostatic chamber (Figure 2a).

Step II. Tests with fouling (Figures 2b, 2c, 2d). When preparing the material for fouling and the procedure for applying it to the surface, the recommendations of [8, 13] were used. All types of fouling were weighed beforehand. Fouling were applied in separate portions. The experiment was carried out for each type of fouling in a stationary mode in a thermostatic chamber. The state of the extremely fouled surfaces is shown in Figures 2b, 2c, 2d.

Measurable parameters and characteristics: temperature of air and refrigerant at the corresponding points of measurement (Figure 1), refrigerant pressure, air velocity, fan power, voltage and amperage of the compressor electric motor and electric heater.

The determined parameters and characteristics include [14]: parameters at the nodal points of the thermodynamic cycle, specific characteristics of the cycle, refrigerant mass flow rate, air cooler refrigerating capacity, power of the compressor and electric heater, condenser heat load, energy efficiency of the machine (COP).

Mathematical model of the condenser characteristics and the machine as a whole based on the experiment results. The basic quantities and the formulas that define them are listed below:

Refrigerant mass flow rate – $M_{ref}$, kg/s.

Energy balance of the thermostatic chamber:

$$M_{ref}^{tch} \cdot q_0 = (U \cdot I_{elheat}) + \kappa F \cdot (T_{amb} - T_{tch}) + \sum P_{fmac} \,, \quad (1)$$

where $q_0$ – specific refrigerating capacity of the cycle (J/g); $U$ – mains voltage (V); $I_{elheat}$ – electric heater amperage (A); $k_F$ – thermal permeability of the thermostatic chamber (W/K); $T_{amb}$ – ambient temperature (K); $T_{tch}$ – temperature in the thermostatic chamber (K); $\Sigma P_{fmac}$ – total power of the air cooler fan motors (W).

Refrigerant mass flow rate from the energy balance of the thermostatic chamber:

$$M_{ref}^{tch} = \frac{(U \cdot I_{elheat}) + \kappa F \cdot (T_{amb} - T_{tch}) + \sum P_{fmac}}{q_0} \quad (2)$$

Energy balance of air condenser:

$$M_{ref}^{cond} \cdot q_{cond} = M_{air} \cdot c_p^{air} \cdot \left(T_{out}^{air} - T_{inl}^{air}\right), \quad (3)$$

where Mair – air mass flow rate (kg/s); $\tilde{n}_{\delta}^{air}$ – air isobaric heat capacity (J/kg·K); qcond – specific condenser heat flux (J/kg); $T_{out}^{air}$ – the temperature of the air inlet to the condenser (K); $T_{inl}^{air}$ – temperature of air outlet from the condenser (K).

$$M_{air} = F_{cr-se} \cdot w_{air} \cdot \rho_{air}, \quad (4)$$

where $F_{cr-se}$ – air condenser cross-section area (m$^2$); *wair* – average air velocity through the condenser (m/s); $\rho_{air}$ – air density (kg/m$^3$).

Refrigerant mass flow rate from the energy balance of the condenser:

$$M_{ref}^{cond} = \frac{M_{air} \cdot c_p \cdot \left(T_{out}^{air} - T_{inl}^{air}\right)}{q_{cond}} \quad (5)$$

Calculated mass flow rate:

$$M_{ref} = \frac{M_{ref}^{tch} + M_{ref}^{cond}}{2} \quad (6)$$

Air cooler refrigerating capacity:

$$Q_0 = M_{ref} \cdot q_0, W \quad (7)$$

Compressor motor power:

$$P_{fmcom} = I_{com} \cdot U, \quad (8)$$

where $I_{com}$ – single-phase motor amperage.

Condenser heat load:

$$Q_{cond} = M_{air} \cdot c_p^{air} \cdot \left(T_{out}^{air} - T_{inl}^{air}\right) \quad (9)$$

Heat flux density:

$$q_{int} = \frac{Q_{cond}}{F_{int}} \quad (10)$$

Real coefficient of performance:

$$COP_{real} = \frac{Q_0}{P_{fmcom}} \quad (11)$$

# Processing data and results trials

The calculating results of the actual coefficient of performance and the refrigerating capacity of the machine depending on the type of fouling and the degree of condenser contamination using the equations of the mathematical model are presented in graphical form in Figures 3–4.

The fouling effects are different. At first, the sand fouling does not have a significant effect on the characteristics, and with the fouling of 1000 g, the characteristics deteriorate sharply. Fluff initially behaves similarly to sand, but from a fouling of 25 g, which corresponds to 400 g of sand, it starts to work as insulation. This entails a sharp deterioration in the energy characteristics of the machine. This phenomenon is explained by the sand and fluff properties.

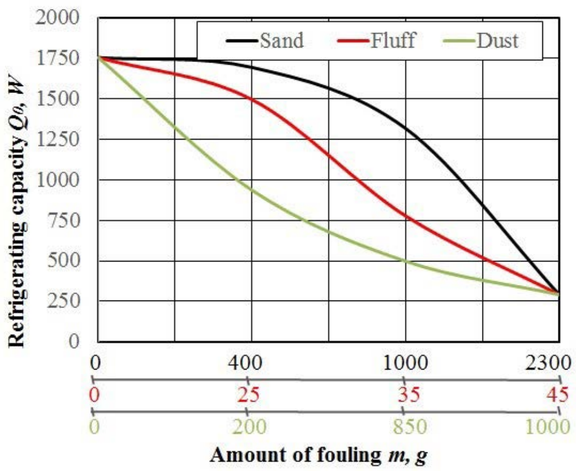



**Figure 3.** Refrigerating capacity depending on the type and amount of fouling

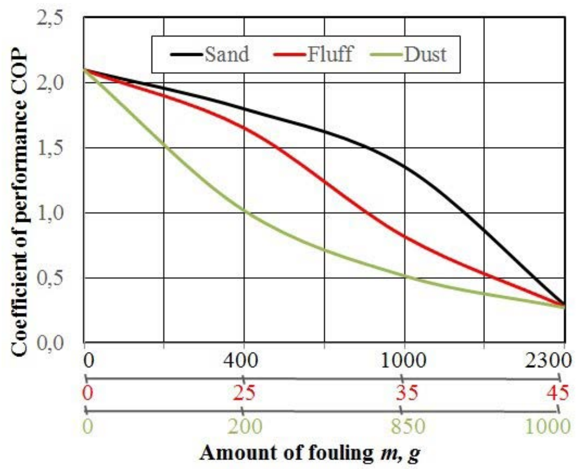
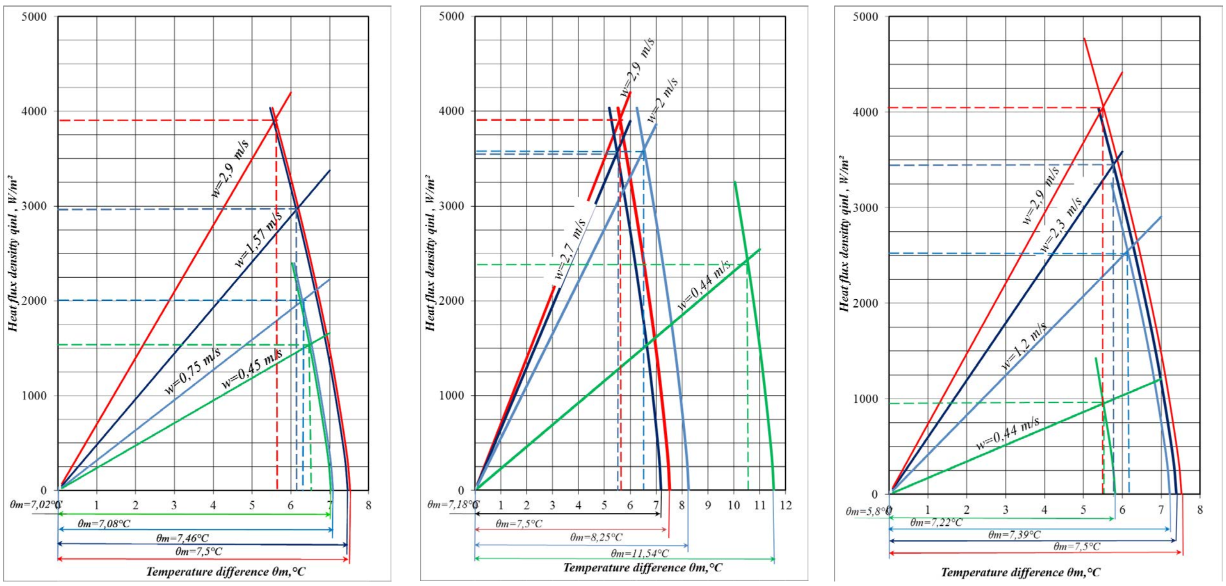



**Figure 4.** Coefficient of performance depending on the type and amount of fouling

Sand is an inorganic substance, the solid phase of which has a high thermal conductivity, thereby increasing the heat exchange surface area. Fluff is an organic substance, the solid phase size of which is microns, and most of the control volume of the heat exchange surface is occupied by air. Organic substance and air together are characterized by low thermal conductivity coefficients, thus, the fluff creates a great thermal resistance. Roadside dust has the greatest negative impact




a) the dust influence

b) the fluff influence

c) the sand influence

**Figure 5.** Graph-analytical method for calculating the heat flux density with real fouling

on machine characteristics. This fouling consists of fine particles of wear on brake pads, tires, vehicle exhaust elements, natural biomasses and mechanical particles in the ambient air, together it turns out to be a good insulating material.

From the machine general characteristics, turn to the individual condenser characteristics: heat flux density $q_{int}$, heat transfer coefficient $k$, pressure drop by air flow $\Delta p$ and the fan operating time coefficient $b$.

The heat flux density calculation was carried out on the basis of experimental data with the use of classical methods for heat exchangers calculating [15, 16].

The incoming air temperature in the experiment remains constant. The qualitative and quantitative composition of the fouling determines the air flow parameters (speed w) and the condensing refrigerant parameters (temperature $T_k$ and pressure $p_k$ of condensation).

The solution to the problem is presented by the graph-analytical method in Figure 5.

Graph a) presents the dust influence; graph b) – the fluff influence, and graph c) – the sand influence. In the graphs, the red line ($w$ = 2.9 m/s) characterizes the heat flux with a clean heat exchange surface of the condenser. All other constructions are individual and depend on the quantitative and qualitative fouling composition, as well as the temperature difference in the apparatus. The calculation results are summarized in Table 1.

**Table 1.** General characteristics of the condenser

| Type surface | Heat flux density $q_{int}$, W/m² | Condenser heat load $Q_{con}$d, W | The total condenser heat transfer coefficient k, W/(m²K) | Pressure drop Δp, Pa |
|---|---|---|---|---|
| clean surface | 3885 | 2800 | 516 | 119.0 |
| sand 400 g | 3700 | 2700 | 514 | 132.4 |
| sand 1000 g | 3650 | 2630 | 442 | 180.6 |
| sand 2300 g | 2450 | 1770 | 212 | 912.4 |
| fluff 25 g | 3450 | 2480 | 466 | 149.6 |
| fluff 35 g | 2600 | 1872 | 360 | 295.6 |
| fluff 45 g | 1300 | 937 | 223 | 833.3 |
| dust 200 g | 2870 | 2272 | 422 | 227.2 |
| dust 850 g | 2025 | 1460 | 286 | 497.5 |
| dust 1000 g | 1650 | 1118 | 221 | 865.6 |

Figures 6–7 illustrate the variations in the air-cooled condenser characteristics: heat load and heat transfer coefficient depending on the type and amount of fouling. From Figures 6–7, it can be seen that roadside dust has a greater effect on the thermal characteristics of the heat exchanger. Figure 7 shows that the nature of the change in the heat transfer coefficient is the same for all types of fouling. With increasing fouling, the heat transfer coefficient decreases sharply. The qualitative composition of the fouling is the main factor that determines the heat exchanger heat load.

The apparatus aerodynamic characteristics are shown in Figures 8–9. Pressure drop have a pronounced dependence on the qualitative composition (Figure 8).

The fan operating time coefficient of the condenser depends on the quantitative and qualitative composition of the fouling (Figure 9).

With a clean surface of the apparatus, the operating time coefficient is $b = 0.3$.

Within the experiment limits, for sand and fluff, the fan operating time coefficient $b = 1.0$ was observed, which corresponded to the maximum filling of the apparatus air section with fouling. In the presence of any roadside dust amount, the fan operating time coefficient practically does not change. The dust settles densely on the entire outer surface, leaving the “open” apparatus cross-section area.

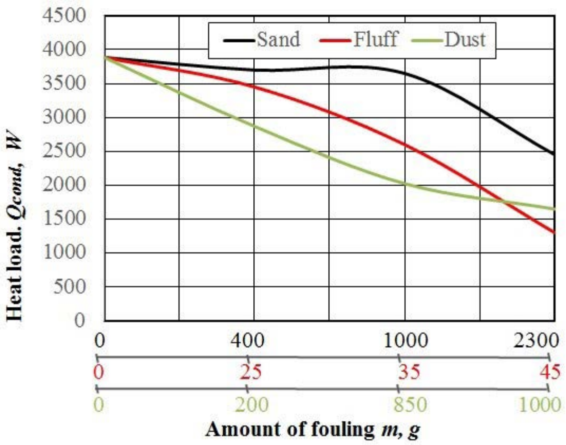



**Figure 6.** Heat load depending on the type and amount of fouling

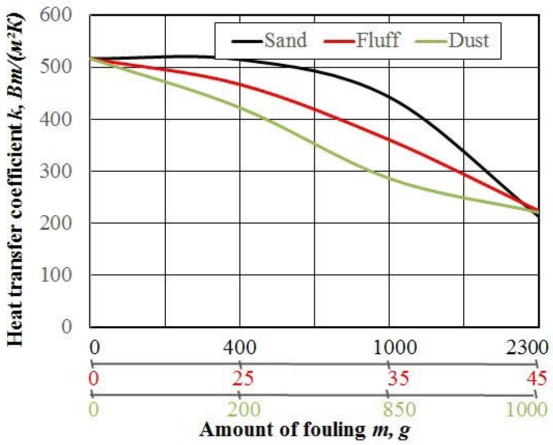



**Figure 7.** Heat transfer coefficient depending on the type and amount of fouling

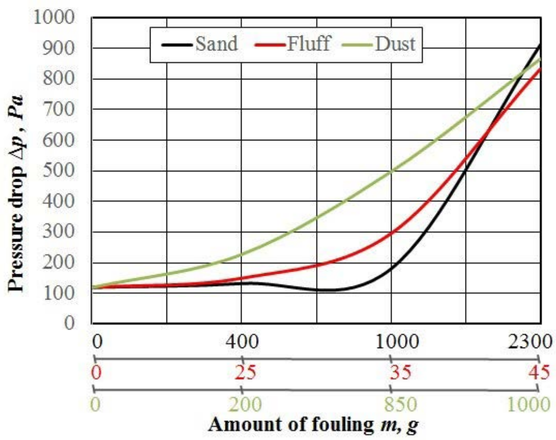



**Figure 8.** Pressure drop depending on the type and amount of fouling

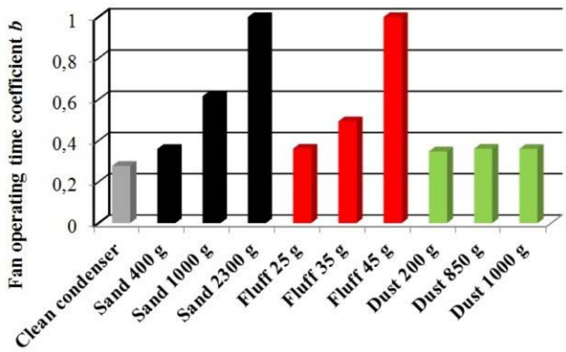



**Figure 9.** Fan operating time coefficient depending on the type and amount of fouling

A step by step method of the experiment conducting with different qualitative and quantitative composition of the fouling made it possible to create structures that are permeable and impermeable to air. The investigated characteristics transformation of the condenser allows to repeat the hypothesis [13] that the fouling is a layer consisting of a solid skeleton and interconnected voids, through which the air flow passes through. This fouling description is consistent with the definition of a "porous body", within which the processes can be described by the laws of porous media [17].

## Conclusions

The experimental bench design in the form of a complete complex of a commercial refrigerated facility (thermostatic chamber and refrigeration system) made it possible to study all the machine elements in real operating conditions.

The set of fouling used in the experiment (roadside dust is picked from condensers on the roadway of the city, fluff is taken during the flowering of trees and bushes, sand is picked from the area of tourist sites in the Middle East) made it possible to study various operating conditions. The qualitative composition of the fouling was the main factor determining the apparatus efficiency.

It was found that from the fouling experimental set, roadside dust has the greatest negative effect on the condenser characteristics and the machine as a whole.

It has been suggested that nature of the process of air flow passing through the investigated fouling can be described as gas flows in porous material. The application of this theory will make it possible to simulate the fouling process of any qualitative composition at the design stage.

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