Study of the influence of fin-plate heat exchanger geometry on dust particle deposition and heat transfer based on numerical calculation

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Abstract. Cooling systems are actively used in computer technology to cool various electronic devices, for example, the central processor units (CPU). CPUs generate heat while operating, which slows down the processing speed of information, and overheating often causes the CPU to shut down or even crash. Cooling systems are designed to remove heat from the CPU. Often, during operation of the cooling system, its main element – the fin-plate heat exchanger becomes covered with a layer of dust, which significantly reduces the rate of heat transfer and can lead to CPU failure. In this work, we carried out numerical modeling of dust particles deposition on the surface of fin-plate heat exchangers of various geometries. We studied the influence of the fin shape (flat or corrugated), as well as the distance between the fins (from 1.75 to 7 mm) on the efficiency of particle deposition and the change in heat flow.

1 Introduction

The modern world cannot be imagined without various electronic devices, which are used in all industries and are the working tools of millions of people [1-3]. During operation, electronic devices, such as central processors, tend to overheat, which, in the best case, leads to a decrease in data processing speed and, in the worst case, to the breakdown of the device. To ensure fast and safe operation of the CPU, cooling systems are used [4]. There are two main methods of CPU cooling: air and liquid. Due to the high heat capacity of water, a liquid cooling system is more efficient than air cooling, but such a system is much more expensive and requires more maintenance during operation. In addition, errors made when installing a liquid cooling system can lead to leaks in the structure and, ultimately, to failure of the CPU. Air cooling systems have become widespread due to their low cost and ease of installation and maintenance [5].

The main element of the cooling system is the heat exchanger. Modern cooling systems usually use plate and fin heat exchangers made of aluminum or copper [6]. The choice of heat exchanger material is determined mainly by thermal conductivity. To quickly and effectively remove heat, it is necessary to use materials with a high thermal conductivity coefficient. Aluminum and copper are distinguished by high thermal conductivity

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coefficients (λ_{al}=200 W/mK and λ_{cop}=400 W/mK) and relatively low costs. In addition to the heat exchanger material, its design has a significant impact on the efficiency of the heat exchanger. As noted earlier, modern cooling systems use plate and fin heat exchangers. However, today there is a trend towards increasing the power of CPUs while miniaturizing them. Modern cooling systems require high efficiency of the heat exchanger and its compactness [7]. It should be noted here that the efficiency of a heat exchanger depends primarily on the heat exchange area, that is, on the surface area of the heat exchanger. Consequently, to increase the efficiency of the heat exchanger, it is necessary to increase its surface area, which in the case of plate and fin heat exchangers leads to an increase in their size. To solve this problem, many researchers propose replacing plate and fin heat exchangers with highly porous ones. Highly porous heat exchangers are open-cell metal foams that are characterized by low density, light weight and a large surface area that is several times larger than the surface area of a finned heat exchanger [8,9], which allows for a significant reduction in the size of the porous heat exchanger and cooling system [10]. The specific surface area of metal foam, depending on the porosity, cell size and diameter of the struts, ranges from 500 to 10,000 m^2/m^3 [11]. Moreover, according to research results [12], increasing the pore density (pores per inch, or PPI) of metal foam from 10 to 40 PPI significantly increases its surface area, from 380 to 1767 m^2/m^3, while keeping the dimensions of the heat exchanger unchanged. The increase in surface area, in turn, led to an increase in heat flux by more than two times [13-17]. However, porous heat exchangers have a significant drawback: they quickly become dusty, which leads to a significant deterioration in thermal-hydraulic characteristics [18]. In addition, porous heat exchangers are several times more expensive than plate heat exchangers, because of which they are not widely used. The main reasons for the deposition of dust particles are gravitational deposition and inertial collisions [19]. Dust often leads to reduced heat flow from the heat exchanger and, as a result, overheating of the CPU and other electronic devices. In addition, dust particles clog the pores, making it difficult for air to pass through the heat exchanger [20-22], and the hydrodynamic properties of the heat exchanger change, which is reflected in an increase in pressure drop due to clogging of the pores. Hooman et al. [23] reported that, compared to pure metal foam, the pressure drop in dust-laden foam increases several times. An increase in pressure drop entails an increase in the fan power required to blow air through the metal foam heat exchanger, which increases electrical energy consumption. Sun et al. [24] conducted experimental studies on the deposition of dust particles on the surface of a heat exchanger. The authors assessed the effect of dust on pressure drop and heat transfer. Research results have shown that dust has a greater effect on pressure drop than on heat transfer. During the period of time from 11 to 76 minutes, during which the heat exchanger was blown by a dusty air stream, the pressure drop doubled while the heat transfer decreased, but not significantly. Hosseini et al. [25] studied the influence of dust particle size (1-1500 μm) and air flow velocity (1-5 m/s) on pressure drop. The authors found that an increase in the size and mass of dust particles contributes to an increase in pressure drop. Air flow speed has different effects on particle deposition: when the speed increases from 1 to 5 m/s, the deposition of small particles doubles, while the deposition of large particles decreases by 20%. Sauret [26] numerically studied the areas of deposition of dust particles on the surface of a heat exchanger when flowing around a dusty air flow. The author found that regardless of the particle size, most of them are deposited at the front of the heat exchanger. The downstream portion of the heat exchanger has a large recirculation zone, causing some particles to return to the heat exchanger. Shikh Anuar et al. [27] experimentally investigated the influence of dust particle size and pore diameter of metal foam on particle deposition. The studies were carried out in a channel partially filled with metal foam. The authors found that the height and location of the foam significantly influence the area of particle deposition. The size of the particles determines their trajectory and deposition. Large particles retain inertia and often collide with obstacles, while small particles move along streamlines. Foams with smaller pores deposit more particles than foams with larger pores. Thus, the influence of heat exchanger structure, dust particle size and air flow velocity on particle deposition and the thermal-hydraulic characteristics of the heat exchanger are known from the literature. The goal of this project is to study how particles land on the surface of a heat exchanger with different shapes. The studies were carried out using the ANSYS Fluent software package (v.19.2). 3D models of heat exchangers with different fin geometries (flat and corrugated) and distances between them (from 1.75 to 7 mm) were built.

2 Materials and methods

Plate heat exchangers are used in cooling systems for microelectronics devices. The amount of heat flow from the heatsink directly affects the speed of the CPU and the solution of engineering problems. During operation, plate heat exchangers are prone to dust, which leads to a decrease in heat flow and a decrease in the speed of the CPU. The dust content of the heat exchanger is assessed by calculating the efficiency of dust particle deposition using formula (1):

The efficiency of particle deposition was determined by formula (1):

$$E = n_{\text{settled}} / n_{\text{started}}, \quad (1)$$

where n_{settled} – the number of dust particles settled on the surface of the radiator.

The deposition of dust particles leads to a reduction in the working area of the heat exchanger (2):

$$F = F_{\text{clean}} - F_{\text{dusty}}, \quad (2)$$

where F_{clean} – surface area of a dust-free heat exchanger, F_{dusty} – dusty surface area.

The surface area of the heat exchanger directly affects the amount of heat that heat exchanger removes from the CPU. The amount of heat flow is calculated using formula (3):

$$\Delta Q = Q_{\text{clean}} - Q_{\text{dusty}}, \quad (3)$$

In this case, the final heat flow from the dusty heat exchanger was calculated using formula (4):

$$Q_{\text{dusty}} = Q_{\text{clean}} / F, \quad (3)$$

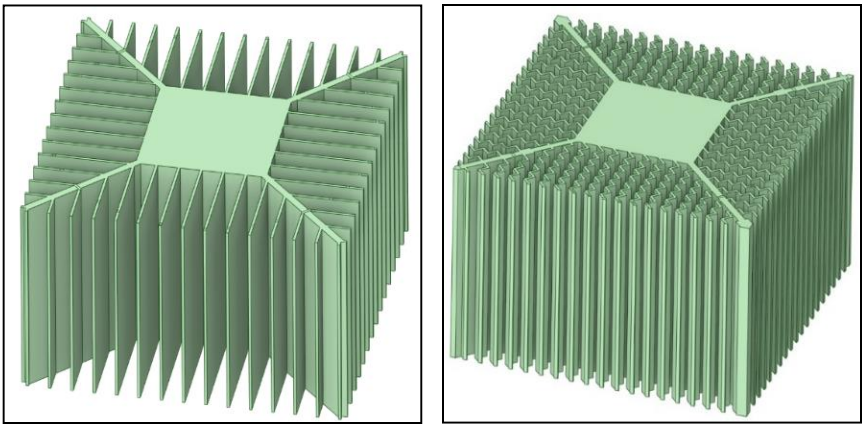
Numerical studies of particle deposition and heat transfer in models of plate heat exchangers were carried out. 3D models of square-shaped heat exchangers with flat and corrugated fins were built; the characteristics are presented in Table 1.

Table 1. Characteristics of radiator models with flat and corrugated fins.

Model name	Fin type	Radiator height, mm	Fin thickness, mm	Distance between fins S, mm
FF1.75*	flat	70	1	1.75
FF3.5	flat	70	1	3.5
FF7	flat	70	1	7

CF1.75**	corrugated	70	1	1.75
CF3.5	corrugated	70	1	3.5
CF7	corrugated	70	1	7

* RFF – radiator with flat fins; 1,2 or 4 – distance between fins
** RCF – radiator with corrugated fins



(a) (b)

Fig. 1. Pictures of radiator models with flat (a) and corrugated (b) fins.

Numerical calculations were carried out using the ANSYS Fluent software package (v.19.2). At the boundaries of the computational domain, the following parameters were set: temperature on the surface of the heater: 353 K, air flow speed: from 1 to 7 m/s in increments of 1 m/s, the diameter of dust particles varied in the range from 10^{-7} to 2 10^{-5} m. Picture of the calculation area is presented in Figure 2.

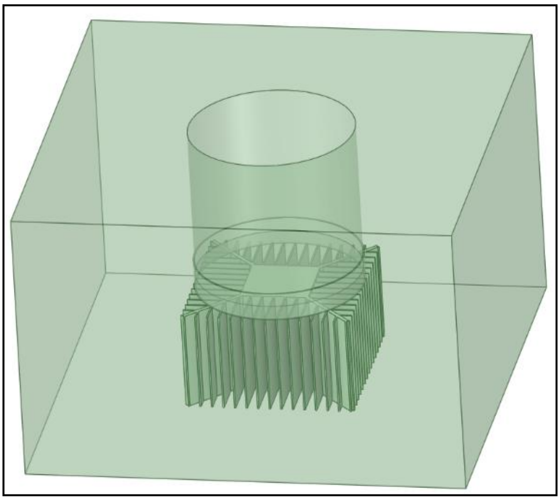


Fig. 2. Picture of the calculation area for the FF7 radiator.

3 Results and discussion

We carried out the numerical calculations of the efficiency of deposition of dust particles on the surfaces of plate heat exchangers with flat and corrugated fins, the distance between which varies from 1.75 to 7 mm. Figure 3 shows the results of calculating the efficiency of particle deposition E depending on the diameter of the dust particle. It is obvious that the deposition efficiency directly depends on the particle diameter: in the range of dust particle sizes from 10^{-6} to 10^{-5} m, there is a sharp increase in the efficiency of particle deposition. Also from the graph we see that the deposition of dust particles on heat exchangers with corrugated fins is much higher: for example, the deposition efficiency of particles with a diameter of 10^{-4} m for the CF1.75 model was 0.99, for the FF1.75 model it was 0.74. It can also be noted that the smaller the distance between the fins, the higher the particle deposition efficiency, for example, for the CF7 model, the deposition efficiency of particles with diameter 10^{-4} m is 0.81, which is 18% lower than for the CF1.75 model.

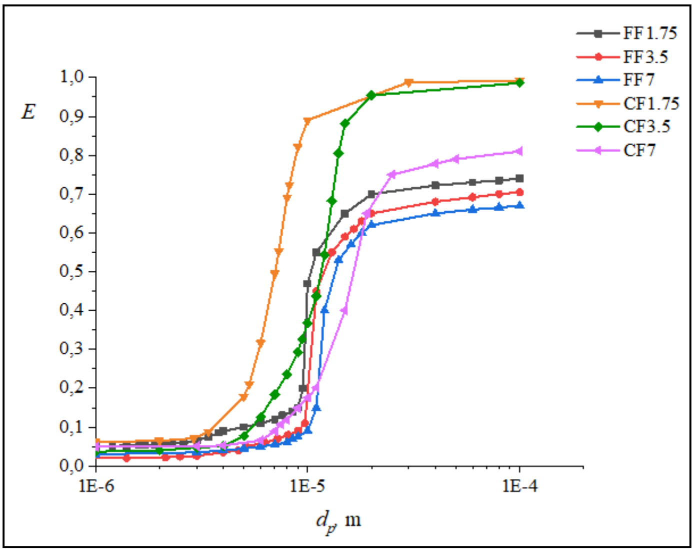


Fig. 3. Efficiency of dust particle deposition on radiators with flat and corrugated fins depending on the particle diameter.

The settling of dust particles on the surface of the heat exchanger leads to a decrease in the working surface area (2). And since surface area is one of the main factors influencing heat transfer, its reduction leads to a decrease in heat flow by a certain amount (3). We carried out the numerical calculations of the change in heat flow from heat exchanger models due to particle settling were carried out. The results are presented in Figure 4. As we can see from the graph, heat exchangers with corrugated fins are more susceptible to changes in the reduction of heat flow, which is explained by the greater efficiency of particle deposition, for example, ΔQ for the FF3.5 model at an air flow rate of 7 m/s was 350 W, for the CF3.5 model it was 551 W. For the same reason, heat exchangers with a smaller distance between the fins show larger ΔQ values, for example, at a speed of 7 m/s for CF7 ΔQ=427 W, for CF1.75 ΔQ=681 W, that is, 60% higher. Thus, we can conclude that heat exchangers with corrugated fins are more susceptible to dust particle settling and heat flow reduction than heat exchangers with flat fins. Increasing the distance between the fins helps to reduce the number of particles deposited on the surface and, therefore, such heat exchangers are less susceptible to a decrease in heat flow.

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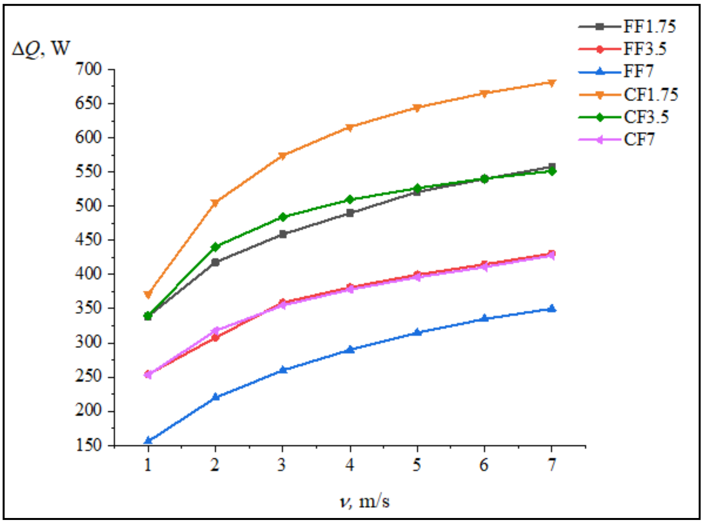

Fig. 4. Change in heat flow (Δ*Q*) from radiators with flat and corrugated fins depending on the air flow rate (ν).

4 Concluions

We carried out the numerical studies of the deposition of dust particles on the surface of fin-plate heat exchangers of various geometries. We built 3D models of heat exchangers with flat and corrugated fins to carry out numerical calculations. The distance between fins varied from 1.75 to 7 mm. The effect of heat exchanger geometry on particle deposition and heat flow variation was investigated. The research results shows that heat exchangers with corrugated fins are more susceptible to dust particles deposition: the efficiency of particle deposition on corrugated fins is up to 20% higher than on flat ones. Consequently, heat exchangers with corrugated fins are more susceptible to heat flux reduction due to dust.

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