Numerical simulation of dust particle deposition and heat transfer in fin-plate radiators

Olga Soloveva[1,*], *Sergei* Solovev[1], *Rozalina* Shakurova[1], and *Timur* Mustafaev[2]

[1]Kazan State Power Engineering University, 51, Krasnoselskaya str., 420066, Kazan, Russia
[2]Kazan National Research Technical University named after A.N. Tupolev – KAI, Kazan, Russia

Abstract. Fin-plate radiators are actively used in cooling systems for microelectronic devices. Radiators often become dusty during operation, which leads to decrease in heat flow and heat dissipation. Consequently, the possibility of device overheating and failure increases. We carried out numerical studies to assess the influence of the radiator geometry on the deposition of dust particles and, as a consequence, the change in heat flow. We built 3D models of plate radiators with different types of fins (flat and corrugated) and the distance between them. The problem of air flow with dust particles flowing around the radiator has been solved. We revealed the dependences of the efficiency of particle deposition and changes in heat flow on the geometry of the radiator, the size of dust particles and the distance between the fins.

1 Introduction

The modern world cannot be imagined without microelectronic devices and systems, which are actively used in everyday life and in many industries [1-3]. During operation, devices consume electricity, part of which is inevitably converted into heat, and therefore the device often overheats. At best, this leads to the device shutting down, at worst, it leads to damage and failure. Overheating is prevented by using cooling systems, which are divided into air and liquid [4,5]. In air systems, the heat from the electronic device is dissipated into the environment by an aluminum heat sink, blown by an air stream. In liquid systems, heat is removed from the radiator by the flow of circulating refrigerant [6]. Due to the high cost of liquid cooling systems as well as the risk of device failure in the event of a leak, air cooling systems have become more widespread. The main element of the system is the radiator, which is a plate or pin heat exchanger made of aluminum [7]. Since the power of modern electronic devices increases every year, scientists in this field are conducting research aimed at increasing the rate of heat transfer by changing the shape and size of the plates and pins [8,9], perforation [10], changing the orientation of the plates and pins relative to the oncoming flow air [11], etc. Haque et al. [12] conducted numerical studies of heat transfer in a radiator with pin fins of rectangular, elliptical and teardrop shapes with perforations. Research results have shown that the hydrothermal efficiency factor (HTPF) of a radiator with elliptical fins is 9-46% higher than the HTPF of radiators of other configurations. The

* Corresponding author: solovyeva.ov@kgeu.ru

cross-sectional geometry of the perforations also had an impact on the HTFP, with the greatest value being achieved in the case of round perforations. Tariq et al. [13] proposed a plate-fin heat exchanger design with longitudinal perforations in the fins. As a result of numerical studies, the authors came to the conclusion that longitudinal perforations make it possible to reduce the pressure drop, metal consumption of the structure, and fan power, while the heat transfer coefficient and Nu number increase by 30-40% compared to an unperforated radiator. Shahsavar et al. [14] investigated the effect of perforation angle on the performance of a pin-fin heat sink. The research results showed that an increase in the angle of inclination of the perforations leads to a decrease in the thermal resistance coefficient R: in the case of an inclination angle of 0° R=7.6 K·m^2/W, in the case of an inclination angle of 45° R=6.4 K·m^2/W. As a result, the highest performance evaluation criterion (PEC) was observed in the radiator model with inclined perforations at an angle of 45°. El-Said et al. [15] investigated the influence of the twist angle of square and hexagonal pin fins on the thermal-hydraulic performance of a radiator. According to the results of the study, an increase in the twist angle helps to reduce the boundary layer, increase the turbulence of the flow, and promote its mixing. A radiator with hexagonal pin fins showed the highest heat transfer coefficient values (75-200 W/m^{2}K) in all tested ranges of twist angle and Reynolds number. Radiators of cooling systems during operation are susceptible to the deposition of dust particles, which, according to research, significantly impairs heat transfer [16-18]. Oguntala et al. [19] studied the deposition of particles on the radiator surface and evaluated the changes in thermal-hydraulic characteristics. The authors concluded that the rate of heat transfer decreases as dust settles and depends on particle size, particle density, and cooling air flow rate. In addition, particle deposition also increases the pressure drop and, therefore, the fan power required to pump air through the radiator. According to the results of studies by Hosseini et al. [20], a decrease in the efficiency of particle deposition is facilitated by an increase in air flow speed, which also has a positive effect on the heat transfer rate. However, a consequence of a high air flow rate is high energy consumption, which is not always advisable. Another known solution to the problem of dust deposition is to change the design of the radiator. Liu et al. [21] proposed a new heat sink design that has self-adjusting fins. As the temperature rises, the angle of the fins changes, thereby enhancing heat dissipation. At the same time, a radiator with such a fin design showed high dust resistance. Thus, in modern scientific literature, problems of heat transfer in radiators have been solved [22,23], the influence of heat exchanger geometry on thermal-hydraulic characteristics has been studied [24], the influence of dust particle deposition on heat transfer. In this work, we numerically study the effect of radiator geometry on the efficiency of dust particle deposition and, as a consequence, the change in heat flow from the radiator.

2 Materials and methods

The settling of dust particles on the surface of the radiator leads to a decrease in its working area and, consequently, to a decrease in the heat flow. To assess the effect of dust on heat removal from the radiator, the efficiency of particle deposition E, the working area of the heat exchanger F, and the change in heat flux ΔQ because of particle deposition were calculated.

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

$$E = n_{\text{settled}} / n_{\text{started}}, \tag{1}$$

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

Based on the number of settled particles, the working area of the heat exchanger F was calculated using formula (2):

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

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

The value ΔQ, which characterizes the change in heat flow as a result of the deposition of dust particles on its surface, was calculated using formula (3):

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

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

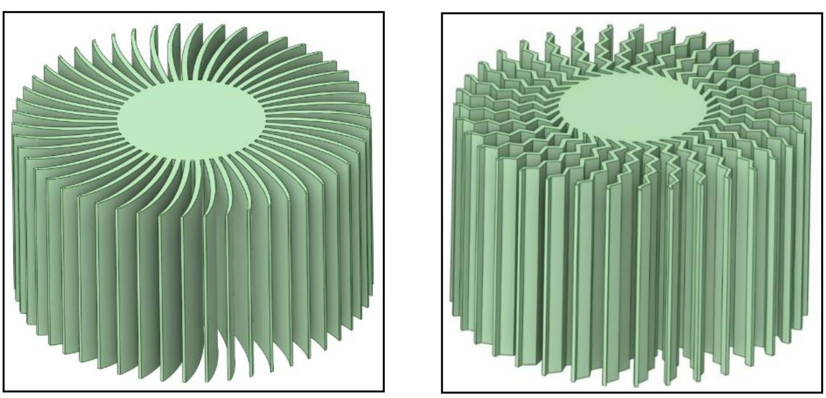
$$Q_{dusty} = Q_{clean}/F, \qquad (3)$$

Research has been carried out on the effect of dust on the efficiency of heat removal from the radiator. To conduct numerical studies, we built 3D models of cylindrical radiators with flat and corrugated fins (Figure 1). The characteristics of the radiators 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**	**Minimum distance between fins S_{min}, mm**	**Maximum distance between fins S_{max}, mm**
RFF1*	flat	70	2	1	4,25
RFF2	flat	70	2	2	8,5
RFF4	flat	70	2	4	17
RCF1**	corrugated	70	2	1	4,25
RCF2	corrugated	70	2	2	8,5
RCF4	corrugated	70	2	4	17

* RFF – radiator with flat fins; 1,2 or 4 – minimum 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: the temperature on the heater surface was 353 K, the air flow speed was varied in the range 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 10^{-2} m Picture of the computational domain is presented in Figure 2.

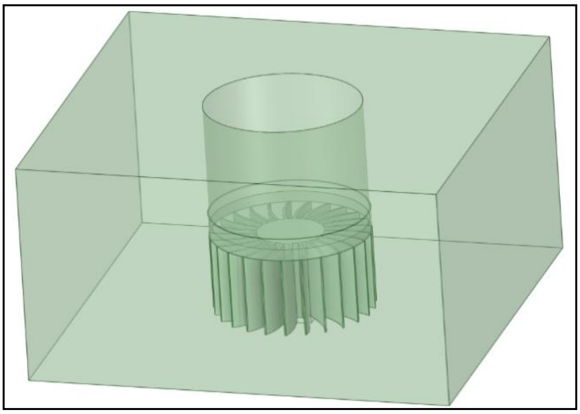


Fig. 2. Picture of the calculation area for the RFF4 radiator.

3 Results and discussion

Numerical calculations of the deposition of dust particles on the surface of the radiator were carried out. The deposition efficiency was studied as a function of particle diameter and radiator geometry. Figure 3 shows the results of calculating the efficiency of particle deposition for the studied radiator models.

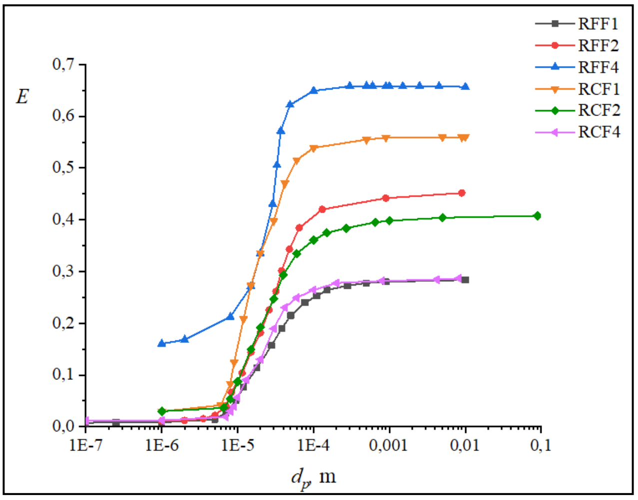


Fig. 3. Efficiency of dust particle deposition on radiators with flat and corrugated fins depending on the particle diameter.

The graph shows that the greater the distance between the fins, the higher the dimensionless efficiency of particle deposition, which for the RFF4 radiator was 0.16-0.66, and for the RFF1 radiator: 0.0076-0.28. Obviously, the larger the diameter of the dust particle, the higher the deposition efficiency. In the case of corrugated fins, the highest deposition efficiency is observed in the RCF1 radiator with the smallest distance between the fins and amounts to 0.029-0.56. The lowest deposition efficiency of 0.012-0.29 is observed in a radiator with a large distance between the fins RCF4. For models RFF2/RCF2 and RFF4/RCF4, particle deposition efficiency is higher for radiators with flat fins (RFF2 and RFF4). The opposite trend was observed for the RFF1/RCF1 models: the RCF1 corrugated fin radiator showed higher deposition efficiency than the RFF1 flat fin radiator. That is, in the case when the radiator has a large number of fins located at a short distance from each other, it is more advisable to use flat fins, since fewer dust particles settle on them. And, conversely, if the radiator has a small number of fins, the distance between which is more than 2 mm, it is more advisable to use a radiator with corrugated fins.

Of all the radiator models studied, the RFF1 model showed the lowest deposition efficiency of 0.283 (at d_p=0.01 m). The highest settling efficiency of 0.657 was observed in the RFF4 model (at d_p=0.01 m).

The settling of dust particles leads to a decrease in the working surface area of the heat exchanger, according to formula (2). In turn, a decrease in heat exchange area leads to a decrease in heat flow. The results of numerical calculations of the change in heat flow (ΔQ) from the radiator due to the settling of dust particles are presented in Figure 4. The highest ΔQ, from 165 to 326 W, over the entire range of air flow rates is observed in the RCF1 model, i.e. a heat exchanger with corrugated fins, the minimum distance between which is 1 mm. The RCF4 model, on the contrary, is less susceptible to changes in heat flow due to dust, which is explained by the low efficiency of dust particle deposition. Based on the calculation results, we can conclude that of all the studied radiator models, the RCF4 model with corrugated fins, the minimum distance between which is 4 mm, has the best characteristics. This model showed low particle deposition efficiency and the smallest change in heat flux from the radiator due to dust.

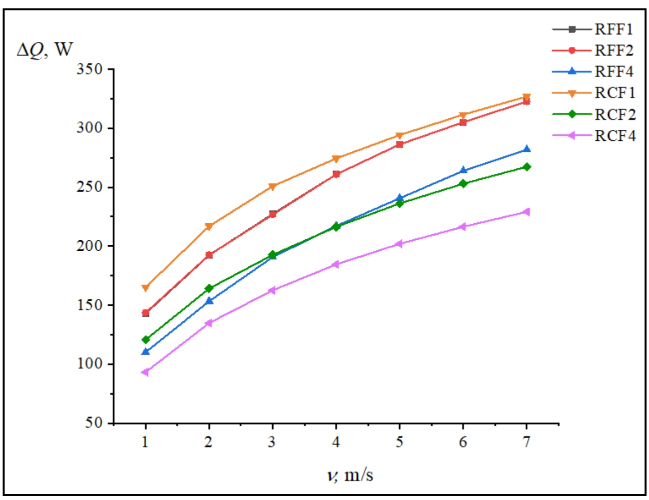


Fig. 4. Change in heat flow (Δ*Q*) from radiators with flat and corrugated fins depending on the air flow rate (ν).

4 Concluions

The work carried out numerical studies of the deposition of dust particles and heat transfer in fin-plate radiators of various geometries. The influence of fin geometry (flat and corrugated), the distance between fins, and the diameter of dust particles on the efficiency of particle deposition and the change in heat flow from the radiator was studied. The results of numerical calculations showed that in radiators with corrugated fins the efficiency of particle deposition is higher, and, accordingly, the change in heat flow is also higher than in radiators with flat fins. Reducing deposition efficiency is achieved by increasing the distance between fins and increasing the air flow rate. A radiator with flat fins provides a lower efficiency of particle deposition, therefore, such radiators are more appropriate to use.

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