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REGULAR ARTICLE

Simulation and Analysis of Heat Dissipation in Compact Routers: Efficiency of Radiators and Case Perforations

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The problem of overheating of information devices to ensure wireless transmission of information is relevant nowadays, because competition among cheap routers does not allow adding expensive cooling systems such as TEC to the design, and installing fans can cause excessive noise. At the same time, the power of miniature processors is increasing to provide high throughput. This leads to a situation where, at an ambient temperature of 30-40 °C, the temperature of the processor with adjacent elements becomes higher than 100 °C, and may cause the device to fail or the case to melt.

In this study, physical-topological simultion of one of the typical keenetic KN-1011 routers for the case of horizontal location was carried out. The distributions of air flows through the case and temperatures on the device elements were obtained for various options for improving the cooling system – adding a radiator of different sizes and additional perforation on the back side.

The main results showed that adding larger heat sinks and additional ventilation holes significantly reduced CPU temperature. Specifically, when using heat sinks of configurations K2 and K3, the CPU temperature dropped to 72 °C and 68 °C, respectively, which is a substantial improvement compared to the base model, where the CPU temperature reached 112 °C. This demonstrates the effectiveness of the proposed cooling methods, allowing optimal thermal management even under heavy loads.

The article also presents a comparative analysis of thermal regimes under different cooling options. In addition to the geometric characteristics of the heat sinks, the additional ventilation holes played a crucial role in enhancing air circulation within the casing. The use of larger heat sinks, combined with casing perforation, reduced CPU temperature by more than 50%, significantly improving the overall performance and reliability of the device.

Keywords: Simulation, Heat transfer, Finite difference method, Router, Processor, Housing, Optimization.

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1. INTRODUCTIONB

Advancements in modern networking technologies and the demand for continuous internet access have led to the rapid proliferation of wireless routers. However, as these devices gain more functionalities, their thermal load also increases. One of the most common reasons for overheating is the operation of embedded processors responsible for data processing and network management.

High temperatures are known to adversely affect the performance and lifespan of electronics, leading to reduced efficiency and shortened device lifespan. Therefore, managing the thermal conditions of routers has become a critical and important task for engineers.

In this research, we investigated a practical engineering problem using the prototype router Keenetic KN-1011 as a case study, employing modeling methods in COMSOL software. This device represents a modern wireless router used to provide stable and fast network access.

This scientific article focuses on studying the issue of processor overheating in routers and developing methods to address it. We analyze various cooling approaches for processors and propose an effective solution involving additional vents in the chassis and radiators of different configurations. Our approach aims to lower device temperatures without compromising its external appearance and ensuring comfortable usage.

2. PROBLEMS

2.1 The Key Aspects

Routers are complex electronic devices that act as intermediaries between different networks for data transmission. They typically consist of a casing, a printed circuit board (PCB), a processor, random access memory (RAM), flash memory, and various communication modules such as wireless and Ethernet interfaces.

Electronic components, particularly processors, operate most efficiently within specific temperature ranges. Typically, the operating temperature range for router processors is defined by the manufacturer and usually spans from 0 °C to 85 °C. Exceeding these values can lead to malfunctions and shorten the device's lifespan.

One of the main causes of router processor overheating

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is their intensive operation. Processors perform significant calculations during data processing and network traffic management, generating a considerable amount of heat. Another contributing factor may be an inefficient cooling system that fails to effectively dissipate heat from the processor.

High processor temperatures can result in several negative consequences. Firstly, it can reduce data processing speeds and consequently slow down router operations. Secondly, prolonged exposure to high temperatures can degrade electronic components, leading to increased likelihood of failures and reduced lifespan due to material degradation.

Additionally, high temperatures can affect the plastic used in the device casing, causing it to lose its mechanical properties. High temperatures may cause bending or damage to the casing components, as well as deformation or detachment of adhesive joints. This not only affects the device's aesthetics but can also compromise the casing's seal and ventilation, exacerbating heat dissipation issues.

2.2 Justification of Research Approaches

There are several methods for cooling processors in routers, including fans, heat pipes, radiators, and additional vents in the casing. Each of these methods has its advantages and disadvantages, and the choice depends on several factors such as cost, efficiency, implementation complexity, and impact on user experience.

The use of fans can be an effective method for active cooling, but it may lead to increased noise levels, energy consumption, and alteration of the device's appearance. Heat pipes can be challenging to implement in devices with limited space.

Using radiators for heat dissipation is a common method; however, they may be ineffective without additional air circulation methods. In our research, we opted against using fans due to their potential impact on user experience through noise levels and energy consumption. We also dismissed heat pipes due to their implementation complexity and limited capabilities in small devices.

Therefore, during the development and implementation of modifications to the device, we adhered to several key requirements. Firstly, any modifications should not compromise the device's external appearance and ergonomics. Secondly, they should not create additional inconveniences for users, such as noise or awkward placement of new cooling elements.

Considering these requirements, we identified the optimal method for cooling the processor in the Keenetic router, ensuring high efficiency without deteriorating the user experience. As a result, radiators and additional vents in the casing were chosen as the optimal cooling method, providing effective heat dissipation with minimal changes to the device's appearance and functionality.

2.3 Preliminary Research

In 2021, a study was conducted with the DN-5327BZ router, which has a similar design and processor, according to the results of which, at an ambient temperature of 40 0C, the processor temperature becomes 100 °C and higher [1]. Some results are shown in Fig. 1.

In the study [2], the issue of CPU cooling in connection with the increasing density of "hot spots" was analyzed. It was proposed to use microchannel liquid cooling systems to improve heat dissipation. Similar to our research, they also focused on increasing the efficiency of CPU cooling. However, unlike our work, they mainly considered high-performance cooling systems such as microchannels, whereas we focused on simpler solutions that do not alter the appearance of the device.

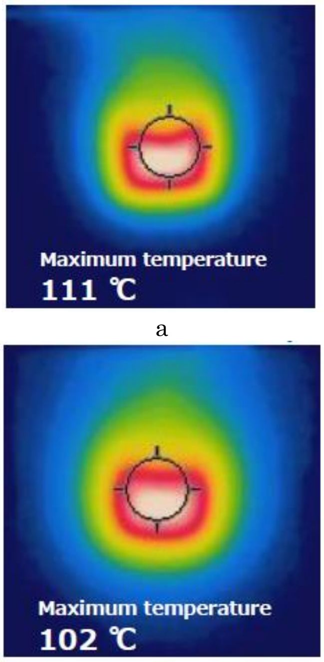


Fig. 1 – Investigation of the temperature field of a vertical router with a processor power of 5 W: PCB conductivity 0.2 W/(m/K) (a), PCB conductivity 0.8 W/(m/K) (b).

Bangalee et al. conducted numerical modeling and optimization of heatsink configurations for CPU cooling using CFD methods [3, 4]. Their study showed that the optimal ratio between the number of heatsink fins, height, and base thickness can reduce the temperature to 51.5 °C, highlighting the importance of proper heatsink geometry in high-performance CPUs. Like our study, the focus was on heatsink shapes and sizes; however, in their case, material parameters were also considered, which was not a key factor in our work.

Sherson developed a test system to analyze the thermal characteristics of porous surfaces in closed liquid cooling systems [5]. His study tested various materials for cooling, but the use of microstructured silver surfaces did not provide the expected improvements in heat transfer compared to copper surfaces. This study emphasizes the importance of material and microstructure selection to enhance heat dissipation, which is also significant for our research. However, unlike the author [5], we did not apply liquid cooling and focused on passive methods such as case perforations and heatsinks.

Yudanto et al. [6] conducted a study based on numerical modeling of CPU cooling system configurations using the CFD method. The study showed that maximum cooling is achieved with copper heatsinks and eight fans in a mixed configuration, allowing the temperature to be reduced to 39.22°C. This is especially important for powerful

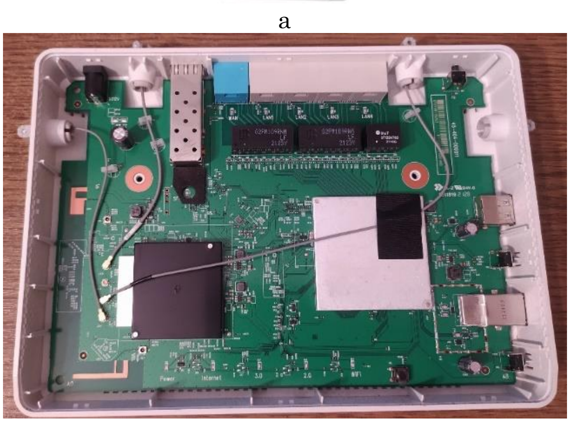
CPUs in small spaces, such as router enclosures. Like in our study, their results confirm the importance of efficient space organization and cooling system geometry, but the difference lies in the fact that we avoided using fans due to their impact on the device's appearance and noise level.

Zhihao Zhang et al. reviewed modern methods of electronic cooling, including both direct and indirect methods [7]. They examined various technologies such as air and liquid cooling, which partially overlap with our research. However, unlike our work, they focused on large-scale cooling systems for high-performance electronics, whereas we concentrated on small devices and simplified cooling methods.

The study by Liu and Yu [8] addressed two-phase liquid cooling, which involved directly submerging the CPU into a liquid. This is significantly different from our approach, where we avoided liquid cooling due to its complexity and high cost. However, similar to our research, they emphasized the importance of effective heat dissipation to maintain stable operation of electronics under high heat flux conditions.

2.4 Methodology of the Research

The first step of our research was the creation of a model of a real prototype of the Keenetic KN-1011 router [9], Fig. 2.



a

b

Fig. 2 – Router KN-1011: general appearance (a), printed circuit board (b)

Key specifications can be found on the manufacturer's website [10]. The most powerful component is the processor, which requires 5 watts of active power [11].

The research prototype KN-1011 served as the basis, with its geometry modeled using COMSOL Multiphysics software. We considered the geometric and physical parameters of the device, including dimensions, materials of the casing, and heat-generating components, particularly the processor.

After creating the model, we conducted numerical simulations to analyze the device's thermal behavior. We studied the temperature distribution inside the casing and compared the obtained results [1].

Following the initial analysis, we made modifications to the model by adding additional vents in the casing and various configurations of radiators for the processor. For each modification scenario, we performed new simulations and compared their results with the base model. Based on these findings, we conducted a detailed analysis, identified optimal parameters for the modifications, and evaluated their effectiveness in reducing the processor temperature. We also assessed the impact of these modifications on the device's appearance and user experience.

Based on our research, we drew conclusions regarding optimal methods for cooling processors in routers and developed recommendations for improving device thermal management.

3. THEORETICAL INFORMATION

Usually, devices similar to the one under study are cooled with the help of free air convection, which blows the built-in radiators. Therefore, for the correct display of the results, free convection was used in the model – a type of substance transfer caused by the action of the pushing force (Archimedean force). The Archimedean force, in turn, is created with the help of the heterogeneous density of the medium of variable composition or temperature.

Gravity was also added to the model, which allows automatically taking into account changes in hydrostatic pressure on vertical boundaries.

$$\rho(\bar{u}\cdot\nabla)\,\bar{u} = \nabla\cdot\left[-p\vec{I}+\vec{K}\right]+\vec{F}+\rho\vec{g} = m\vec{a}\ , \qquad (3.1)$$

$$\nabla\cdot(\rho\,\bar{u}) = 0\ , \qquad (3.2)$$

where ρ – density of the environment, $\bar{u}$ – flow velocity field, p – pressure, $\vec{K}$ – the viscous stress tensor, $\vec{F}$ – volumetric force, $\vec{I}$ – identity matrix, $\vec{g}$ – Acceleration of gravity.

Only the processor is taken into account as a heat source in the model. The dimensions of the processor are 50 × 40 × 1.6 mm. Set power 5 W, pressure 1 atm, ambient temperature 40 °C (taking into account heating from other heat sources). At the beginning of the simulation, the temperature of all areas of the model is equal to the temperature of the surrounding medium.

$$\rho C_p\,\bar{u}\cdot\nabla T + \nabla\cdot\vec{q} = Q + Q_{ted}\,, \qquad (3.3)$$

$$\vec{q} = -k\nabla T\ , \qquad (3.4)$$

where: ρ – density of the environment, C_P – heat capacity, $\bar{u}$ – flow velocity field, T – temperature, $\vec{q}$ – heat flow of convective heat exchange, Q – heat sources (energy), Q_{ted} – thermoelastic damping, k – thermal conductivity.

The model also takes into account heat exchange through radiation, in which thermal radiation is interpreted as energy transfer between boundaries and external heat sources, where the medium does not participate in radiation, that is, it is completely transparent.

When studying radiation, all external open boundaries of the model are involved. Radiation spreads in all directions from the radiator, the radiation coefficient of surfaces $\varepsilon = 0.85$ [12]. A transparency condition has been added for all voids in the design of the router. It is assumed that no radiation passes through the surface.

The basic equations for calculating surface-to-surface radiation are given below:

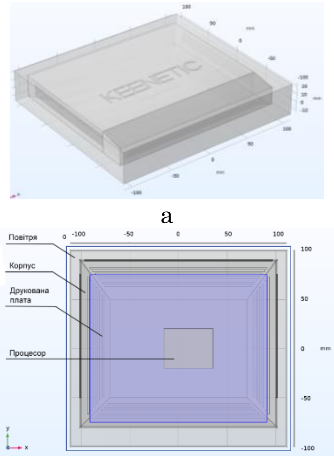
$$e_b(T) = n^2 \sigma T^4 , \qquad (3.5)$$

$$-\vec{n} \cdot \vec{q} = \varepsilon (G - e_b(T)) , \qquad (3.6)$$

where e_b – the total radiative power of the blackbody, T – temperature, σ – Stefan-Boltzmann constant, $\vec{q}$ – radiation power of the heat source, $\vec{n}$ – normal vector, ε – surface emissivity, G – total radiation power.

4. MODEL DEFINITION

The initial geometry of the model (without modifications) is presented in Fig. 3.

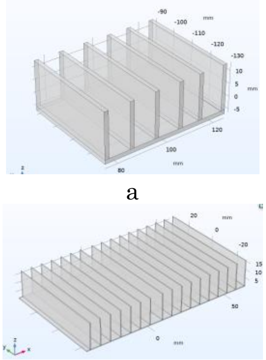


a

b

Fig. 3 – Virtual physical- topological model of the KN-1011 router of horizontal construction: general view in isometry (a), model elements taken into account (b)

Models of routers with three different designs of radiators were investigated: K1 (Fig. 4, a), K2 (Fig. 4, b) and K3 (Fig. 4, c).



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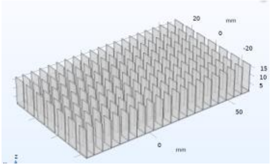


c

Fig. 4 – Designs of radiators used in the study (a – K1, b – K2, c – K3)

In the K2 and K3 designs, in addition to increasing the overall dimensions of the radiator, the thickness of the ribs was also reduced, due to which their number and, accordingly, the total surface area of the radiator was increased.

A study of the effect of additional holes on the back wall of the router housing was also conducted. The view of the model from all sides is presented in Fig. 5.

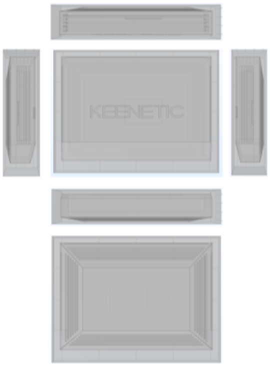


Fig. 5 – Cases: basic (a), with additional perforation

The dimensions of the model elements are given in Table. 1.

Element		Length, mm	Width, mm	Height, mm	Thickness, mm
Processor		50	40	–	1.6
Substrate		180	150	–	1.6
Compound		200	160	30	1
Air		200	180	40	–
Radiator	K1	50	40	17	1.6
	K2	100	60	17	0.5
	K3	100	60	17	0.5

The width of the holes in the compound is 2 mm.

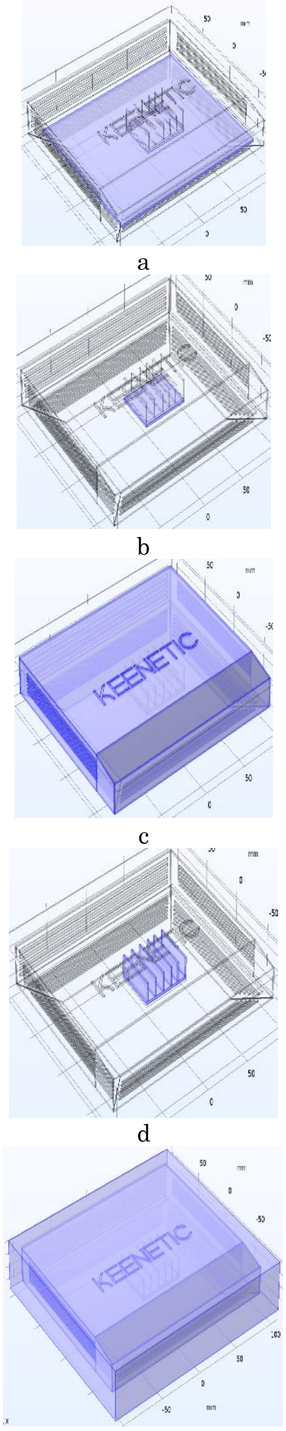
The width of the holes in the ribs of the radiator in K3 is 3 mm.

Materials were used (see Fig. 6).

The model employed two multiphysics couplings: non-isothermal flow and heat exchange with surface-to-surface radiation.

Non-isothermal flow refers to flows with varying temperatures. When a fluid undergoes temperature changes, its material properties such as density and viscosity also change accordingly. In some situations, these changes can be significant enough to significantly affect the flow field. Thus, heating of the air around the processor directly influences flow characteristics.

The multiphysics coupling of heat exchange with surface-to-surface radiation was added to account for heat exchange through radiation at boundaries, where the surrounding environment does not participate in radiation (transparent medium). This allows us to observe the impact of thermal waves on the casing walls and include radiation heat losses in the model.



a

b

c

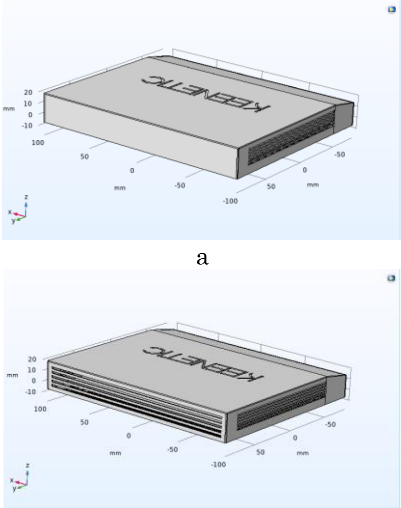
d

e

Fig. 6 – Materials used in the model and domains of their application: printed circuit board - fiberglass FR-4 (a), processor – silicon (b), case – acrylic plastic (c), radiator (all designs) – aluminum (d), surrounding medium-higher – air (d)

5. RESULTS AND DISCUSSION

A study was carried out for 5 configurations of the geometry of the radiator and the body of the device: the initial model without a radiator, the radiator of the K1 design without and with the perforation of the body, and the radiators of the K2 and K3 designs with the perforation of the body. The shapes of the cases are shown in Fig. 7.



a

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Fig. 7 – Cases: basic (a), with additional perforation (b).

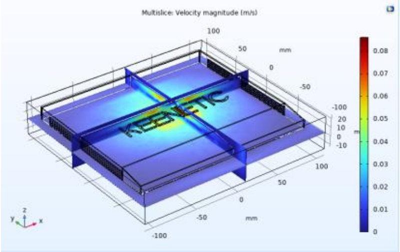
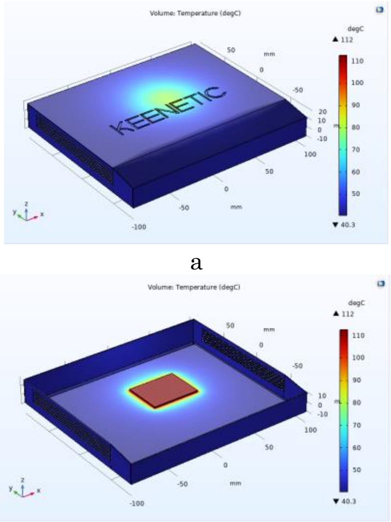


Fig. 8 – Convective air flow velocity distribution with a translucent view of the model without a radiator, two vertical two-dimensional sections through the center of the processor and one horizontal section are shown



a

b

Fig. 9 – Temperature distribution for the model without a radiator: the whole case (a), the case with the cover removed after calculations (b)

Two related physical-topological problems were solved: determination of the distribution of speed and pressure in a laminar convective flow of air moving through holes in the case without external influence except gravity, and the distribution of the thermal field on the processor, radiators, textolite, the case and the surrounding in the air

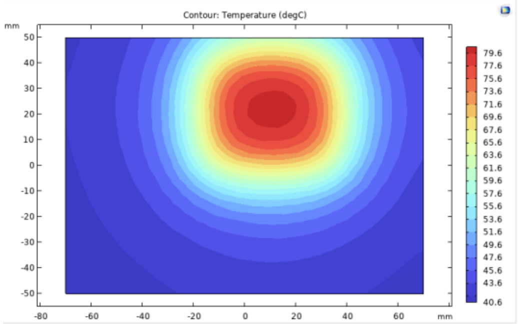
Three-dimensional graphs with distributions of flow rates and temperature are shown in Fig. 8 and 9, respectively.

As observed, the airflow is highest near the processor, reaching 0.085 m/s. The maximum temperature reaches 112 °C directly on the processor. In this case, the two- and one-dimensional distributions will provide more informative insights. Specifically, the heating profiles of the casing, top cover, and bottom cover are shown in Fig. 10.

As indicated, temperatures along the edges equalize to approximately ambient temperature. Approaching the processor on both sides, temperatures rise to 80 °C.

Fig. 11 illustrates temperature distributions directly on the processor. The temperature varies slightly across the processor surface but exceeds the recommended operating temperature.

An additional graph, Fig. 12, displays specific energy losses due to radiation and specific energy dissipation across the processor and device surfaces.



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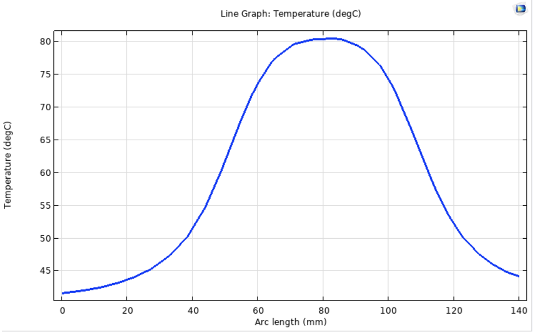

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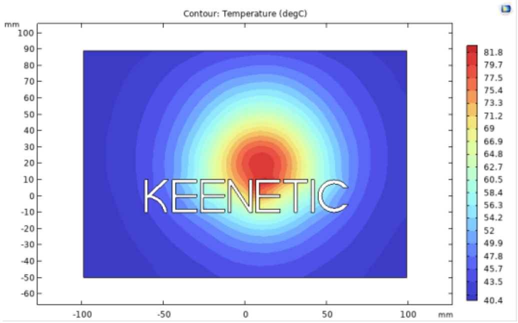

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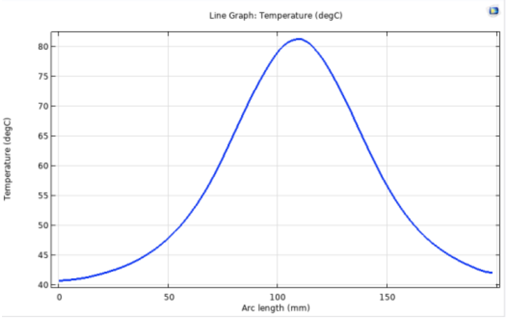
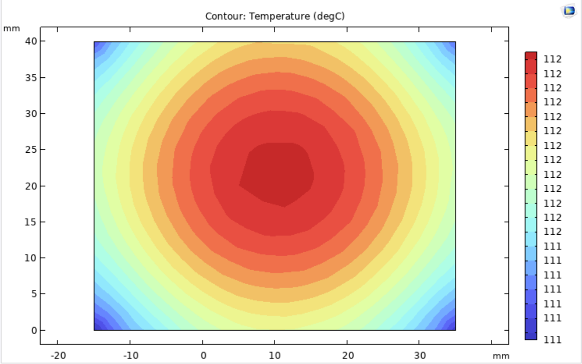


d

Fig. 10 – Temperature distributions: two-dimensional plot of the bottom cover (a), one-dimensional plot of the bottom cover (above the center of the processor) (b), two-dimensional plot of the top cover (c), one-dimensional plot of the top cover (above the center of the processor) (d)



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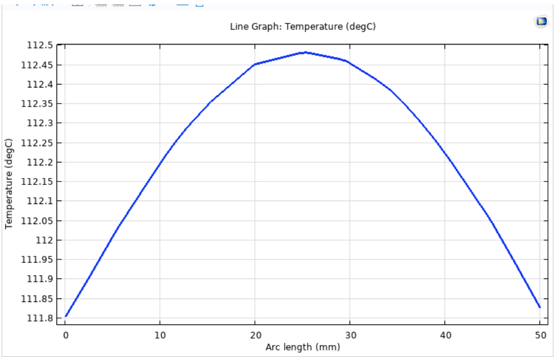
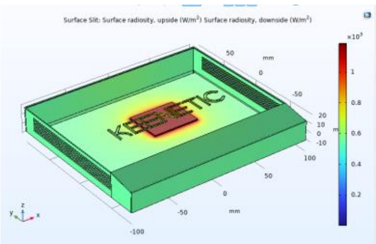


b

Fig. 11 – Temperature distributions on the processor: two-dimensional graph (a), one-dimensional graph (b)



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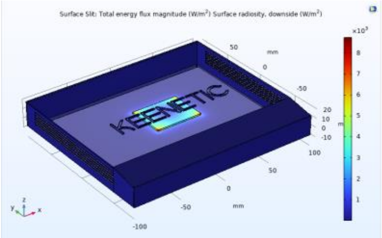
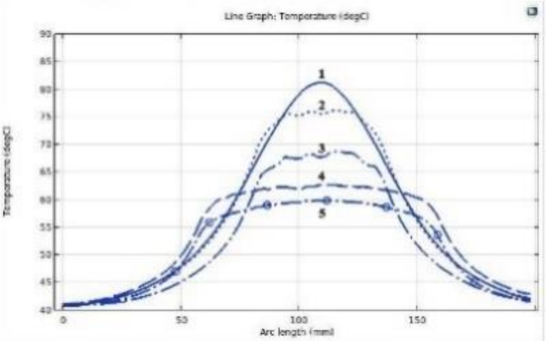


b

Fig. 12 – Specific energies: radiation radiation (a), energy removal (b)

From the above, for comparison, we are interested in the temperature distribution for the existing designs on the most thermally loaded parts: the surfaces of the top and bottom covers and the surface of the processor. Comparison data are shown in Fig. 13.

In the initial design, the processor temperature reaches 112 °C, which is unacceptably high and could lead to deformation of the PCB and damage to contacts. Adding a small radiator K1 reduces the temperature to 96 °C without additional vents in the casing and to 97 °C with additional vents. Large radiators designs K2 and K3, combined with perforations in the casing, lower the temperature to 72 °C and 68 °C respectively. These figures are significantly improved and indicate, in particular, less dependence on perforation and strong correlation with radiator design and size.



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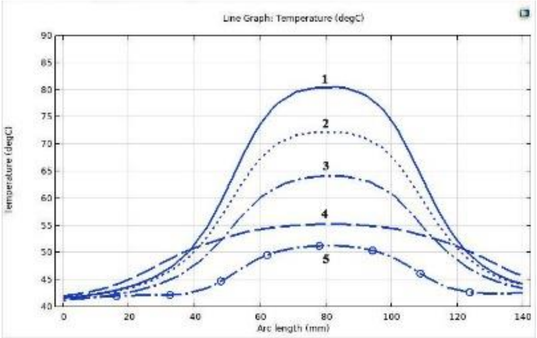

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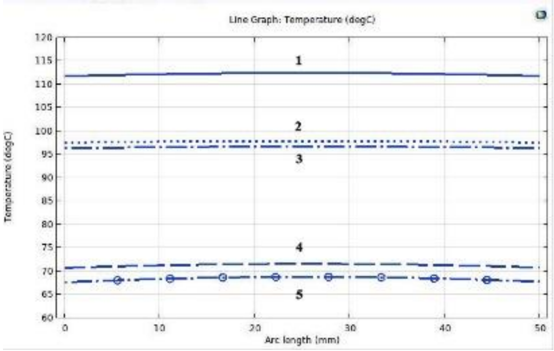

c

Fig. 13 – Temperature distributions along the middle parts of the elements: top cover (a), bottom cover (b), processor surface (c). Solid line – no modifications, dotted line – K1 radiator without additional holes, dashed line – K2 radiator, dash-dotted line – K1 radiator with additional holes, dash-dotted line with markers – K3 radiator

6. CONCLUSION

A physical-topological model of the Keenetic KN-1011 router was constructed: a replicated design from a real prototype to enable comparison with previous physical results, along with 4 modified versions featuring three different sizes of radiators and additional perforations in the casing. The modeling results indicate that at an ambient temperature of 40 °C, the presence of either a small or large radiator allows reducing the processor surface temperature from 112 °C to 97 °C and 72 °C (by 21 % and 56 %), respectively. Adding perforations to the router in the horizontal position lowers the temperature by a few percentage points.

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Моделювання і аналіз тепловідведення в компактних маршрутизаторах: ефективність радіаторів та корпусних перфорацій

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Проблема перегріву інформаційних пристроїв для забезпечення бездротового передавання інформації є актуальною у наш час, оскільки конкуренція серед дешевих роутерів не дає можливості додавати до конструкції дорогі системи охолодження по типу елементів Пельтьє, а встановлення вентиляторів може спричинити надмірний шум. У той же час, зростає потужність мініатюрних процесорів для забезпечення високої пропускної здатності. Це призводить до ситуації, коли при температурі навколишнього середовища 30-40 °C температура процесора з прилеглими елементами стає вищою за 100 °C, і може спричинити вихід з ладу приладу або плавлення корпусу.

У даному дослідженні проведено фізико-топологічне моделювання одного з типових маршрутизаторів keenetic KN-1011 для випадку з горизонтальним розташуванням, отримано розподіли потоків повітря через корпус і температури по елементам пристрою для різних варіантів покращення системи охолодження – додавання радіатора різного розміру та додаткової перфорації на тильній стороні.

Основні результати дослідження показали, що додавання радіаторів великого розміру та додаткових вентиляційних отворів може значно знизити температуру процесора. Зокрема, за використання радіаторів конструкцій К2 і К3 температура процесора знижувалася до 72 °C та 68 °C відповідно, що суттєво покращує тепловідведення порівняно з базовою конструкцією, де температура процесора досягала 112 °C. Це свідчить про ефективність запропонованих методів охолодження, які дозволяють підтримувати оптимальний температурний режим навіть при високих навантаженнях.

Також у статті представлено порівняльний аналіз теплових режимів при різних варіантах охолодження. Окрім геометричних характеристик радіаторів, важливу роль відіграють додаткові вентиляційні отвори, які сприяють циркуляції повітря всередині корпусу. Використання великих радіаторів у поєднанні з перфорацією корпусу дозволило знизити температуру процесора більш ніж на 50 %, що суттєво покращує загальну продуктивність та надійність пристрою.

Ключові слова: Моделювання, Теплоперенос, Метод кінцевих елеметнів, Роутер, Процесор, Корпус, Оптимізація.