# Design Of Advanced Reconfigurable Computer Systems With Liquid Cooling

Ilya Levin[1], Alexey Dordopulo[2]🖂, Alexander Fedorov[3], Yuriy Doronchenko[4]

[1-4] Scientific Research Centre of Supercomputers and Neurocomputers Co Ltd,
Taganrog, Russia
`levin@superevm.ru, dordopulo@superevm.ru🖂, ss24@mail.ru, doronchenko@superevm.ru`

**Abstract.** The paper covers problems of design of reconfigurable computer systems with a liquid cooling system. Design principles of liquid cooling systems of open and closed types are specified, and their comparative analysis is presented. It is shown that open type liquid cooling systems are the most acceptable for high-performance computer systems design. Architecture features of various immersion liquid cooling systems are analyzed; selection criteria of the main cooling system components are given. The paper presents the results of modelling, prototyping and experimental verification of the main technical solutions for our energy-efficient computational module with liquid cooling. The design of the computational module, designed on the base of the modern FPGAs of Xilinx UltraScale series, is presented. It is shown that the developed solutions have power reserve for design of advanced computer systems, based on the new UltraScale+ FPGA family. For the UltraScale+ FPGAs it is necessary to perform some modifications, concerning both the layout of the main computational circuit board and the design of the computer unit and its cooling system. The upgraded design of our advanced computer unit with liquid cooling is presented.

**Keywords:** Liquid Cooling; Reconfigurable Computer Systems; FPGAs; High-Performance Computer Systems; Energy Efficiency.

## 1 Introduction

One of the most effective approaches, which provide high real performance of a computer system is adaptation of its architecture to a structure of a solving task. In this case a special-purpose computer device is created. It hardwarily implements all computational operations of the information graph of the task with the minimum delays. Here, we have a contradiction between the implementation of the special-purpose device and its general-purpose use for solving tasks from various problem areas. It is possible to eliminate these contradictions, combining creation of a special-purpose computer device with a wide range of solving tasks, within a concept of reconfigurable computer systems (RCS) based on FPGAs that are used as a principal computational resource [1].

RCS, which contain FPGA computational fields of large logic capacity, are used for implementation of computationally laborious tasks from various domains of science and technique, because they have a considerable advantage in their real performance and energetic efficiency in comparison with cluster-like multiprocessor computer systems.

The leading Russian vendor of high-performance RCS is Scientific Research Centre of Supercomputers and Neurocomputers (SRC SC & NC, Taganrog, Russia), which produce a wide range of products: from completely stand-alone small-size reconfigurable computers (the Caleano product line), desktop or rack computational modules (Rigel, based on Xilinx Virtex-6 FPGAs, Taygeta, based on Xilinx Virtex-7 FPGAs) to computer systems which consist of a set of computer racks, placed in a specially equipped computer room (RCS-7).

The main distinctive feature of the RCS, produced in SRC SC & NC, is high board density and high (not less than 90%) filling of FPGAs that, as a result, provide high specific energetic efficiency of such systems [5].

Practical experience of maintenance of large computer complexes based on RCS proves that air cooling systems have reached their heat limit. Continuous increasing of the circuit complexity and the clock rate of each new FPGA family leads to considerable growth of power consumption and to growth of the maximal operating temperature on chip. So, for the XC6VLX240T-1FFG1759C FPGAs of a computational module (CM) Rigel-2 the maximum overheat of FPGAs relative to the environment temperature of $25^{o}$C in an operating mode and with the power of 1255 Watt, consumed by the CM, is $33.1^{o}$C, i.e. the maximum temperature of the FPGA chip of the CM Rigel-2 is $58.1^{o}$C. For the XC7VX485T-1FFG1761C FPGAs of the CM Taygeta the maximum overheat of FPGAs relative to the environment temperature of $25^{o}$C in an operating mode and with the power of 1661 Watt, consumed by the CM, is $47.9^{o}$C, i.e. the maximum temperature of the FPGA of the CM Taygeta is $72.9^{o}$C. If we take into account that the permissible temperature of FPGA functioning, which provides high reliability of the equipment during a long operation period, is $65...70^{o}$C, then it is evident, that maintenance of the CM Taygeta requires decrease of the environment temperature.

According to the obtained experimental data, conversion from the FPGA family Virtex-6 to the next family Virtex-7 leads to growth of the FPGA maximum temperature on $11…15^{o}$C. Therefore further development of FPGA production technologies and conversion to the next FPGA family Virtex Ultra Scale (power consumption up to 100 Watt for each chip) will lead to additional growth of FPGA overheat on 10…15°C. This will shift the range of their operating temperature limit (80…85°C), which means negative influence on their reliability when chips are filled up to 85-95% of available hardware resource. This circumstance requires a quite different cooling method which provides keeping of performance growth rates of advanced RCS.

## 2 Liquid Cooling Systems For Reconfigurable Computer Systems

Development of computer technologies leads to design of computer technique which provides higher performance, and hence, more heat. Dissipation of released heat is provided by a system of electronic element cooling, that transfers heat from the more heated object (the cooled object) to the less heated one (the cooling system). If the cooled object is constantly heated, then the temperature of the cooling system grows and in some period of time will be equal to the temperature of the cooled object. So, heat transfer stops and the cooled object will be overheated. The cooling system is protected from overheat with the help of cooling medium (a heat-transfer agent). Cooling efficiency of the heat-transfer agent is characterized by heat capacity and heat dissipation. As a rule, heat transfer is based on principles of heat conduction, that require a physical contact of the heat-transfer agent with the cooled object, or on principles of convective heat exchange with the heat-transfer agent, that consists in physical transfer of the freely circulating heat-transfer agent.

To organize heat transfer to the heat-transfer agent, it is necessary to provide heat contact between the cooling system and the heat-transfer agent. Various *heat-sinks* – facilities for heat dissipation in the heat-transfer agent are used for this purpose. Heat-sinks are set on the most heated components of computer systems. To increase efficiency of heat transfer from an electronic component to a heat-sink, a *heat interface* is set between them. The heat interface is a layer of heat-conducing medium (usually multicomponent) between the cooled surface and the heat dissipating facility, used for reduction of heat resistance between two contacting surfaces. Modern processors and FPGAs need cooling facilities with as low as possible heat resistance, because at present even the most advanced heat-sinks and heat interfaces cannot provide necessary cooling if an air cooling system is used.

Till 2013 air cooling systems were used quite successfully for cooling supercomputers. But due to growth of performance and circuit complexity of microprocessors and FGAs, used as components of supercomputer systems, air cooling systems have practically reached their limits for designed perspective supercomputers, including hybrid computer systems. Therefore the majority of vendors of computer technique consider liquid cooling systems as an alternative decision of the cooling problem. Today liquid cooling systems are the most promising design area for cooling modern high-loaded electronic components of computer systems.

A considerable advantage of all liquid cooling systems is heat capacity of liquids which is better than air capacity (from 1500 to 4000 times), and higher heat-transfer coefficient (increasing up to 100 times). To cool one modern FPGA chip, 1 $m^3$ of air or 0.00025 $m^3$ (250 ml) of water per minute is required. Transfer of 250 ml of water requires much less of electric energy, than transfer of 1 $m^3$ of air. Heat flow, transferred by similar surfaces with traditional velocity of the heat-transfer agent, is in 70 times more intensive in the case of liquid cooling than in the case of air cooling. Additional advantage is use of traditional, rather reliable and cheap components such as pumps, heat exchangers, valves, control devices, etc. In fact, for corporations and companies, which deal with equipment with high packing density of components operating at high temperatures, liquid cooling is the only possible solution of the problem of cooling of modern computer systems. Additional possibilities to increase liquid cooling efficiency are improvement of the initial parameters of the heat transfer agent: increasing of velocity, decreasing of temperature, providing of turbulent flow, increasing of heat capacity, reducing of viscosity.

Heat transfer agent of liquid cooling systems of computer technique is liquid such as water or any dielectric liquid. Heated electronic components transfer heat to the permanently circulating heat transfer agent – liquid, which, after its cooling in the external heat exchanger, is used again for cooling of heated electronic components. There are several types of liquid cooling systems. Closed loop liquid cooling systems have no direct contact between liquid and electronic components of printed circuit boards [6-7]. In open loop cooling systems (liquid immersion cooling systems) electronic components are immersed directly into the cooling liquid [8-9]. Each type of liquid cooling systems has its own advantages and disadvantages.

In closed loop liquid cooling systems all heat-generating elements of the printed circuit board are closed by one or several flat plates with a channel for liquid pumping [10-11]. So, for example, cooling of a supercomputer SKIF-Avrora [12] is based on a principle “one cooling plate for one printed circuit board”. The plate, of course, had a complex surface relief to provide tight heat contact with each chip. Cooling of a supercomputer IBM Aquasar is based on a principle “one cooling plate for one (heated) chip”. In each case the channels of the plates are united by collectors into a single loop connected to a common heat-sink (or another heat exchanger), usually placed outside the computer case and/or rack or even the computer room. With the help of the pump the heat transfer agent is pumped through the plates and dissipates heat, generated by the computational elements, by means of the heat exchanger. In such system it is necessary to provide access of the heat transfer agent to each heat-generating element of the calculator, what means a rather complex “piping system” and a large number of pressure-tight connections. Besides, if it is necessary to provide maintenance of the printed circuit boards without any serious demounting, then the cooling system must be equipped with special liquid connectors which provide pressure-tight connections and simple mounting/demounting of the system.

In closed loop liquid cooling systems it is possible to use water or glycol solutions as the heat transfer agent. However, leak of the heat transfer agent can lead to possible ingress of electrically conducting liquid to unprotected contacts of printed circuit boards of the cooled computer, and this, in its turn, can be fatal for both separate electronic components and the whole computer system. To eliminate failures the whole complex must be stopped, and the power supply system must be tested and dried up. Control and monitoring systems of such computers always contain multiple internal humidity and leak sensors. To solve the leak problem a method, based on negative pressure of liquid in the cooling system, is frequently used. According to this method, water is not pumped in under pressure, it is pumped out, and this practically excludes leak of liquid. If air-tightness of the cooling systems is damaged, then air ingresses the system but no leak of liquid happens. Special sensors are used for detection of leaks, and modular design allows maintenance without stopping of the whole system. However, all these capabilities considerably complicate design of hydraulic system.

Another problem of closed loop liquid cooling systems is a dew point problem. In the section of data processing the air is in contact with the cooling plates. It means that if any sections of these plates are too cold and the air in the section of data processing is warmer and not very dry, then moisture can condense out of the air on the plates. Consequences of this process are similar to leaks. This problem can be solved ether by hot water cooling, which is not effective, or by control and keeping on the necessary level the temperature and humidity parameters of the air in the section of data processing, which is complicated and expensive.

The design becomes even more complex, when it is necessary to cool several components with a water flow proportionally to their heat generation. Besides branched pipes, it is necessary to use complex control devices (simple T-branches and four-ways are not enough). An alternative approach is use of an industrial device with flow control, but in this case the user cannot considerably change configuration of cooled computational modules.

Advantages of closed loop liquid cooling systems are**:**

- use water or water solutions as the heat transfer agent which are available, have perfect thermotechnical properties (heat transfer capacity, heat capacity, viscosity), simple and comparatively safe maintenance;

- the large number of unified mechanisms, nodes and details for water supply systems, which can be used;

- great experience of maintenance of water cooling systems in industry.

However, closed loop liquid cooling systems have a number of significant disadvantages, which restrict their widespread use:

- difficulties with detection of the point of water leakage;

- catastrophic consequences that are the result of leakages not detected in time;

- technological problems of leakage elimination (a required power-off of the whole computer rack, that is not always possible and suitable);

- required support of microclimate in the computer room (a dew point problem);

- a problem of cooling of all the rest components of the printed circuit board of the RCS computational module. Even slight modification of the RCS configuration requires a new heat exchanger;

- a problem of galvanic corrosion of aluminum heat exchangers or a problem of mass and dimensions restrictions for more resistant copper heat exchangers (aluminum is three times as lighter than copper);

- air removal from the cooling system that is required before starting-up and adjustment, and during maintenance;

- complex placement of the computational modules in the rack with a large number of fittings required for plug-in of every computational module;

- necessity of use of a specialized computer rack with significant mass and dimension characteristics.

In open loop liquid cooling systems the heat transfer agent is the principal component, a dielectric liquid based, as a rule, on a white mineral oil that provides much higher heat storage capacity of the heat transfer agent, than the one of the air in the same volume. According to their design, such system is a bath filled with the heat transfer liquid (also placed into a computer rack) and which contains printed circuit boards and servers of computational equipment. The heat, generated by electronic components, is dissipated by the heat transfer agent that circulates within the whole bath. Advantages of immersion liquid cooling systems are simple design and capability of adaptation to changing geometry of printed circuit boards, simplicity of collectors and liquid connectors, no problems with control of liquid flows, no dew point problem, high reliability and low cost of the product.

The main problem of open loop liquid cooling systems is chemical composition of the used heat transfer liquid which must fulfil strict requirements of heat transfer capacity, electrical conduction, viscosity, toxicity, fire safety, stability of the main parameters and reasonable cost of the liquid.

Open loop liquid cooling systems have the following advantages:

- insensibility to leakages and their consequences, capability of operating even with local leakages of the heat transfer agent;

- insensibility to climate characteristics of the computer room;

- solution of the problem of cooling of all RCS components, because the printed circuit board of the computational module is immersed into the heat transfer agent;

- capability of modification of the configuration of the printed circuit board of the computational module without modification of the cooling system;

- simplicity of hydraulic adjustment of the system owing to lack of complex system of collectors;

- possibility of use of unified mechanisms, nodes and details, produced for hydraulic systems of machine industry, and know-how of maintenance of electrical equipment that uses dielectric oils;

- increasing of the total reliability of the liquid cooling system.

Disadvantages of open loop liquid cooling systems are the following:

- necessity of an additional pump and heat exchange equipment for improvement of thermotechnical properties (heat transfer capacity, heat capacity, viscosity) of the heat transfer agent. Here special dielectric organic liquids are used as the heat transfer agent;

- necessity of training of maintenance staff and keeping increased safety precautions for work with the heat transfer agent;

- necessity of more frequent cleaning of the computer room because of high permeability of the heat transfer agent, especially in the case of leakage;

- necessity of special equipment for scheduled and emergency maintenance operations (mounting/demounting of the computational module, loading/unloading of the heat transfer liquid, etc.);

- increasing of the maintenance cost because of necessity of regular changeout of the heat transfer liquid when its service life is over and necessity of heat transfer agent management (transporting, receipt, accounting, storing, distribution, recovery of the heat transfer agent, etc.) in the corporation.

Estimating the given advantages and disadvantages of the two liquid cooling systems we can note more weighty advantages of open loop cooling systems for electronic components of computer systems. In this connection for advanced RCS it is reasonable to use direct immersion of heat-generating system components into the mineral oil based liquid heat transfer agent.

At present the technology of liquid cooling of servers and separate computational modules is developed by many vendors and some of them have achieved success in this direction [9-11]. However, these technologies are intended for cooling computational modules which contain one or two microprocessors. All attempts of its adaptation to cooling computational modules which contain a large number of heat generating components (an FPGA field of 8 chips), have proved a number of shortcomings of liquid cooling of RCS computational modules.

The main disadvantages of existing technologies of immersion liquid cooling [10-14] for computational modules which contain FPGA computational fields are:

- poor adaptation of the cooling system for placement into standard computer racks;

- inefficiency of cooling of electronic component chips with considerable (over 50 Watt) heat generation;

- the thermal paste between FPGA chips and heat-sinks is washed out during long-term maintenance;

- the system of cooling liquid circulation inside the module is designed for one or two chips, but not for an FPGA field, and this fact leads to considerable thermal gradients;

In the systems, based on the IMMERS [9] technology, all cooling liquid is circulating within a closed loop though the chiller, and this fact leads to some problems;

- necessity of computer complex maintenance stoppage for withdrawal separate components and devices;

- necessity of use of a power specialized pump and hydraulic equipment adapted to the cooling liquid;

- a complex system for control of cooling liquid circulation which causes periodic failures;

- high cost of the cooling liquid which is produced by the only one manufacturer.

The presented disadvantages can be considered as an inseparable part of other existing open loop liquid cooling systems because cooling of RCS computational modules which contain not less than 8 FPGA chips has some specific features in comparison with cooling of a single microprocessor.

The special feature of the RCS produced in Scientific Research Centre of Supercomputers and Neurocomputers is the number of FPGAs, not less than 6-8 chips on one printed circuit board and high packing density. This considerably increases the number of heat generating components in comparison with microprocessor modules, complicates application of the technology of direct liquid cooling IMMERS along with other end solutions of immersion systems, and requires additional technical and design solutions for effective cooling of RCS computational modules.

Use of open liquid cooling system is efficient owing to the heat-transfer agent characteristics and the design and specification of the used FPGA heat-sinks, pump equipment, heat-exchangers.

The heat-transfer agent must have the best electric strength, high heat transfer capacity, the maximum possible heat capacity and low viscosity.

The heat-sink must provide the maximum possible surface of heat dissipation, must allow circulation of the heat-transfer agent through itself, a turbulent heat-transfer agent flow in itself, manufacturability. The specialists of SRC SC & NC have performed heat engineering research and suggested a fundamentally new design of a heat-sink with original solder pins, which create a local turbulent flow of the heat-transfer agent. The used thermal interface cannot be deteriorated or washed out by the heat-transfer agent. Its coefficient of heat conductivity must remain permanently high. The specialists of SRC SC & NC have created an effective thermal interface which fulfills all specified requirements. Besides, the technology of its coating and removal was also perfected.

The pump equipment is also not the least of the components of the CM cooling system. The principal criteria which must be taken into account are the following:

- provision of design operating parameters;

- outline dimension and coordinated placement of the input and the output fittings;

- the pump must be suitable for interaction with oil products with a specified viscosity and chemical composition;

- continuous maintenance mode;

- minimal vibrations;

- the pump must have the minimal permissible positive suction head;

- the protection class of the pump electric motor must be not less than IP-55.

The heat-exchanger is also an important component of the cooling system. Its design must be compact and must provide efficient heat exchange. Research, performed by the scientific team of SRC SC & NC proved that the most suitable design of the heat-exchanger is a plate-type one, designed for mineral oils cooling in hydraulic systems of industrial equipment.

The liquid cooling system must have a control subsystem which contains sensors of level, flow, temperature of the heat-transfer agent, and a temperature sensor for cooling components.

## 3 Reconfigurable Computer System ”SKAT” Based On Xilinx Ultrascale FPGAS

Since 2013 the scientific team of SRC SC and NC has actively developed the domain of creation of next-generation RCS on the base of their original liquid cooling system for computational circuit boards with high packing density and the large number of heat generating electronic components. The basis of design criteria of the computational module (CM) of next-generation RCS with an open loop liquid cooling system are the following principles:

- the RCS configuration is based on a computational module with the 3U height and the 19” width and with self-contained circulation of the cooling liquid;

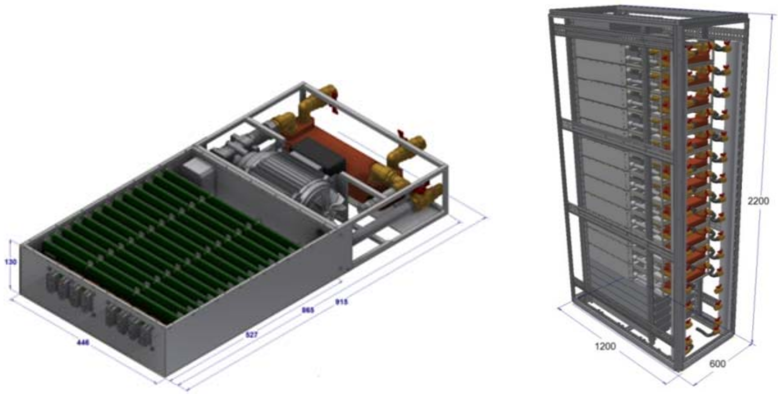
- one computational module can contain 12-16 computational circuit boards (CCB) with FPGA chips;

- each CCB must contain up to 8 FPGAs with dissipating heat flow of about 100 Watt from each FPGA;

- a standard water cooling system, based on industrial chillers, must be used for cooling the liquid.

The principal element of modular implementation of an open loop immersion liquid cooling system for electronic components of computer systems is a reconfigurable computational module of a new generation (see the design in Fig. 1-a). The CM casing of a new generation consists of a computational section and a heat exchange section. In the casing, which is the base of the computational section, a hermetic container with dielectric cooling liquid and electronic components with elements that generate heat during operating, is placed. The electronic components can be as follows: computational modules (not less than 12-16), control boards, RAM, power supply blocks, storage devices, daughter boards, etc. The computational section is closed with a cover.

The computational section adjoins to the heat exchange section, which contains a pump and a heat exchanger. The pump provides circulation of the heat transfer agent in the CM through the closed loop: from the computational module the heated heat-transfer agent passes into the heat exchanger and is cooled there. From the heat exchanger the cooled heat-transfer agent again passes into the computational module and there cools the heated electronic components. As a result of heat dissipation the agent becomes heated and again passes into the heat exchanger, and so on. The heat exchanger is connected to the external heat exchange loop via fittings and is intended for cooling the heat-transfer agent with the help of the secondary cooling liquid. As a heat exchanger it is possible to use a plate heat exchanger in which the first and the second loops are separated. So, as the secondary cooling liquid it is possible to use water, cooled by an industrial chiller. The chiller can be placed outside the server room and can be connected with the reconfigurable computational modules by means of a stationary system of engineering services. The design of the computer rack with placed CMs is shown in Fig. 1-b.



a) b)

**Fig. 1.** The design of the computer system based on liquid cooling (a – the design of the new generation CM, b – the design of the computer rack)

The computational and the heat exchange sections are mechanically interconnected into a single reconfigurable computational module. Maintenance of the reconfigurable computational module requires its connection to the source of the secondary cooling liquid (by means of valves), to the power supply or to the hub (by means of electrical connectors).

In the casing of the computer rack the CMs are placed one over another. Their number is limited by the dimensions of the rack, by technical capabilities of the computer room and by the engineering services.

Each CM of the computer rack is connected to the source of the secondary cooling liquid with the help of supply return collectors through fittings (or balanced valves) and flexible pipes; connection to the power supply and the hub is performed via electric connectors.

Supply of cold secondary cooling liquid and extraction of the heated one into the stationary system of engineering services connected to the rack, is performed via fittings (or balanced valves).

For testing technical and technological solutions, and for determination of expected technical and economical characteristics and service performance of the designed high-performance reconfigurable computer system with liquid cooling, we designed a number of models, experimental and technological prototypes. Fig. 2-b shows the prototype of a new generation CM “Skat”. For this CM a new design of a CCB with high packing density was created.

**Fig. 2.** The prototype of the new generation CM

The CCB of the advanced computational module contains 8 Kintex UltraScale XCKU095T FPGAs; each FPGA contains a specially designed thermal interface and a low-height heatsink for heat dissipation.

We have designed an immersible power supply unit which provides DC/DC 380/12 V transducing with the power up to 4 kWatt for 4 CCB.

The computational section of the CM "SKAT" contains 12 CCB with the power up to 800 Watt each, 3 power supply units. Besides, all boards are completely immersed into an electrically neutral liquid heat-transfer agent.

For creation of an effective immersion cooling system a dielectric heat-transfer agent was developed. This heat-transfer agent has the best electric strength, high heat transfer capacity, the maximum possible heat capacity and low viscosity.

The heat exchange section contains pump components and the heat exchanger, which provide the effective flow and cooling of the heat-transfer agent. The design height of the CM is 3U.

The performance of one next-generation CM "SKAT" is increased in 8.7 times in comparison with the CM "Taygeta". Such qualitative increasing of the system specific performance is provided by more than triple increasing of the system packing density owing to original design solutions, and increasing of the clock frequency and the FPGA logic capacity.

Experimental results prove that the complex of the developed solutions concerning the immersion liquid cooling system provide the temperature of the heat-transfer agent not more than 30 °C, the power of 91 Watt for each FPGA (8736 Watt for the CM) in the operating mode of the CM. At the same time, the maximum FPGA temperature during heat experiments does not exceed 55 °C. This proves that the designed immersion liquid cooling system has a reserve and can provide effective cooling for the designed RCS based on the advanced Xilinx UltraScale+ FPGA family.

## 4 Advanced Reconfigurable Computer System ”SKAT+” Based On Xilinx Ultrascale+ FPGAS

Use of the UltraScale+ FPGAs, which have been implemented on the base of the 16-nm technology 16FinFET Plus and produced by Xilinx since 2017, will provide up to triple growth of the computational performance owing to the growth of clock frequency and FPGA circuit complexity; the size of the computer system remains unchanged. However, in spite of reduction of relative energetic consumption owing to new technological standards of FPGAs manufacturing, and owing to a certain power reserve of the designed liquid cooling system, it is possible to expect a new approach of FPGA operating temperatures to their critical values.

Besides, the new FPGAs of the UltraScale+ family have larger geometric sizes. The size of the FPGAs of the RCS “SKAT” is 42.5x42.5 mm. The size of the FPGAs, which are going to be placed into the RCS “SKAT+”, is 45x45 mm. Due to this circumstance it is impossible to use the existing design of the CCB, because the width of the printed circuit board will become larger and therefore will not fit for the standard 19’’ rack.

In this connection it is necessary to modify the designed open liquid cooling system and the CCB design that will lead to modification of the whole CM.

At present the scientific team of SRC of SC & NC is working on a design of an advanced RCS based on the Xilinx UltraScale+ FPGAs. Owing to these works, concerning modification of the cooling system, we are going to solve the following problems:

1. Increase of effective surface of heat-exchange between FPGAs and the heat-transfer agent.

2. Increase of the performance of the heat-transfer agent supply pump.

3. Increase of reliability of the liquid cooling system with the help of immersed pumps.

4. Experimental improvement of the heat-sink optimal design.

5. Experimental improvement of the technology of thermal interface coating.

We have designed a prototype of an advanced computational module with a modified immersed cooling system (Fig. 3). The distinctive feature of the new design is immersed pumps and the considerable reliability growth of the CM owing to reduction of the number of components and simplification of the cooling system. According to our plans, the heat exchange section will contain only the heat exchanger. We are working on experimental research of various pump equipment which can operate in the heat-exchange agent.

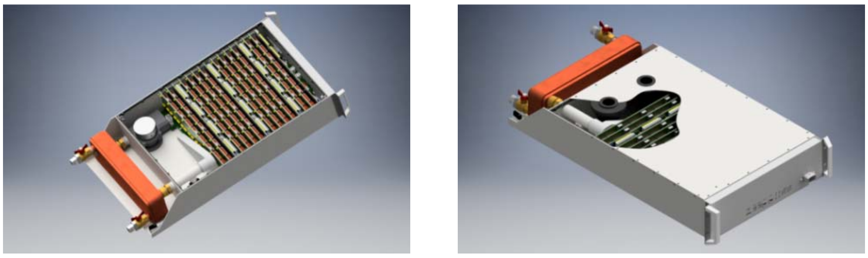


**Fig. 3.** A prototype of a computational module with a modified immersed cooling system

During modification of the CCB design we have created a prototype of an advanced board shown in Fig. 4. The CCB contains 8 UltraScale+ FPGAs of high circuit complexity. To provide placement of a new CCB into a 19” rack possible, it is necessary to exclude its CCB controller from its structure. The CCB controller was always implemented as a separate FPGA and provided access to FPGA computational resources of the CCB, FPGA programming, condition monitoring of the CCB resources.

Even if an FPGA is rather small, its resource grows permanently for each new family. At the same time, the variety of functions of the CCB controller expands slightly. As a result, at present, the resource required for implementation of all functions of the CCB controller is only some percent from the logic capacity of the used FPGAs. In this connection we assume further implementation of the CCB controller as a separate FPGA unreasonable. One of FPGAs of the computation field will perform all functions of the controller.

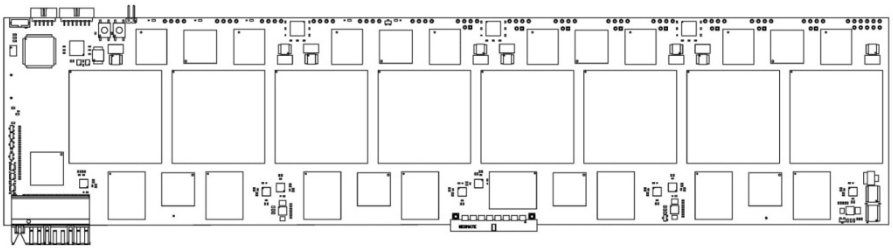


**Fig. 4.** The prototype of the CCB modified packing

So, owing to breakthrough technical solutions which we have got during design of the RCS “SKAT” with the immersed liquid cooling system, we can develop this direction of high-performance RCS design, and after some design improvements we can create a computer system which provides a new level of computational performance.

## 5 Conclusion

Use of air cooling systems for the designed supercomputers has practically reached its limit because of reduction of cooling effectiveness with growing of consumed and dissipated power, caused by growth of circuit complexity of microprocessors and other chips. That is why use of liquid cooling in modern computer systems is a priority direction of cooling systems perfection with wide perspectives of further development. Liquid cooling of RCS computational modules which contain not less than 8 FPGAs of high circuit complexity is specific in comparison with cooling of microprocessors and requires development of a specialized immersion cooling system. The designed original liquid cooling system for a new generation RCS computational module provides high maintenance characteristics such as the maximum FPGA temperature not more than 55 °C and the temperature of the heat-transfer agent not more than 30 °C in the operating mode. Owing to the obtained breakthrough solutions of the immersion liquid cooling system it is possible to place not less than 12 CMs of the new generation with the total performance over 1 PFlops within one 47U computer rack. Power reserve of the liquid cooling system of the new generation CMs provides effective cooling of not only existing but of the developed promising FPGA families Xilinx UltraScale+ and UltraScale 2.

Since FPGAs, as principal components of reconfigurable supercomputers, provide stable, practically linear growth of RCS performance, it is possible to get specific performance of RCS, based on Xilinx Virtex UltraScale FPGAs, similar to the one of the world best cluster supercomputers, and to find new perspectives of design of super-high performance supercomputers.

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