Increasing efficiency safety of cooling systems in a floating nuclear power plant

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Abstract. In order to increase the reliability and safety of a floating nuclear power plant, the research proposes to apply closed-loop cooling systems for floating nuclear power plants’ cooling. A ship hull is proposed to be used as a surface of the heat exchanger, known as a ship hull heat exchanger. This paper presents detailed study on the effect of the ship hull angle on the heat transfer coefficient and measures to improve the heat transfer coefficient. It is concluded that application of gas-liquid flows to the seaside surfaces of the ship hull is one of the most effective ways of improving the heat transfer coefficient.

1. Introduction

The use of small size nuclear power plants is advisable for regions where there is a lack of electricity supply with their own energy resources or supply of traditional fuels causes a great problem for this area. Furthermore, to develop a nuclear power plant for electricity and heat supply on navigable water areas in the above mentioned problematic regions can be a promising solution [1]. Fig.1 gives an example of a floating nuclear power plant. Modern industry has the technology for the design and building of nuclear ships and associated equipment. Thus, it is possible to replicate smaller scale standard nuclear power generation units in the design and building of a floating nuclear power plant, which is more technologically challenging than that of the onshore nuclear power plant, where the concrete construction is a fundamental structure.

Figure 1. A floating nuclear power plant.

Floating nuclear power plants can be considered as a new model of energy provision. The model is developed based on the nuclear shipbuilding technology. A floating nuclear power plant should be designed for a year-round reliable operation. The floating nuclear power plant considered in this paper is a shore-tied ship designed in accordance with the rules and requirements of the Russian Maritime
Register of Shipping. The floating nuclear power plant consists of two KLT-40S nuclear reactors [1]. The demonstration versions of these reactors were successfully used in the nuclear ice-breakers "Taimyr" and "Vaigach" and the transport ships "Sevmorput".

The current development has been focused on improvement of the reliability, efficiency and environmental safety of nuclear reactors operating on such ships to ensure that the reactors of the floating nuclear power plant have sufficient and effective protection and safety, including passive protection (independent of human intervention or automation). Low-enriched nuclear fuel is used to meet the requirements of the International Atomic Energy Agency.

One of the most critical systems serving a floating nuclear power plant is the cooling system. Open-loop cooling systems have been widely applied to ships. As shown in Fig.2, the power plant is cooled with distilled water. In the sea water loop of the open-loop cooling system, corrosive sea water often with solids in the sea water causes a reliability degradation of the heat exchanger, thence the power plant. In many cases, clogging of system elements is a significant problem, particularly when operating in contaminated areas with shallow water, ice sludge, etc.

![Figure 2. The scheme of an open-loop of the power plant.](image)

A solution to this problem is to use a closed-loop cooling system as shown in Fig. 3. By using an exclusive reception of outboard water, a closed-loop cooling system improves the performance of the power plant and prevents adverse environmental impacts [3]. The number of loops in a closed-loop cooling system is important. If it is a single loop, there is a high risk of radioactive pollution in case of breakage of the heat exchanger or pipes. As shown in Fig. 3, the use of systems with two or three loops ensures a safe shut down of the power plant in an emergency situation, such as breakage of the seawater heat exchanger. However, there is also no need to increase the number of loops, because an increase in the number of loops leads to a decrease of temperature difference $\Delta t$ between the heat exchanger seaside surface and the outboard water. As a result, the required heat transfer area has to be increased.

![Figure 3. The scheme of a closed-loop of the power plant.](image)

In this study, the ship’s hull is used as a heat exchanger surface of the final loop taking the outboard water as a coolant. The advantages of the ship hull heat exchanger (SHHE) are an easy design and virtually maintenance-free in operation. The SHHE efficiency determines largely the efficiency of the closed-loop cooling system as a whole. The worst operational condition of the SHHE is when the ship operates in still and warm water. In this case, the heat transfer to the outboard water is dominated by free convection. Fedorovsky [5] has proved that the heat transfer coefficient of free convection depends strongly on the angle of the slope of the heat transfer surface. Fig. 4 illustrates the results obtained from the experiment, when the heat transfer coefficient of free convection decreases as the slope angle is reduced. Temperature difference $\Delta t$ was defined by the difference between the temperature of the heat exchanger outside surface and the temperature of the outboard water.
2. Theoretical aspects

Theoretical study of a two-phase flow is challenging due to the difficulty in obtaining adequate and accurate mathematical models [2-7]. There is a necessity to conduct laboratory experiment work to evaluate parameters in the models.

The following is governing equations for a free convection system describing the heat transfer, energy conservation, continuity and the motion of the flow in the boundary [6]:

\[
\begin{align*}
\alpha &= -\frac{\lambda}{t_x} \left( \frac{\partial t}{\partial x} \right) \\
& \\
& \\
& \\
\begin{cases}
 u_x \frac{\partial t}{\partial x} + u_y \frac{\partial t}{\partial y} = a \left( \frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} \right) \\
\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} = 0 \\
 u_x \frac{\partial u_x}{\partial x} + u_y \frac{\partial u_y}{\partial y} = -\nu \frac{\partial^2 u_x}{\partial y^2} + g \cdot \beta \cdot \Delta t
\end{cases}
\]

Additional parameters are required to describe gas-liquid jet flows, such as air bubbles’ motion and their interaction with the surrounding water. Research has been carried out to investigate the interaction of gas-liquid flows with heat transfer surfaces [5-12]. Since a large number of assumptions are taken for the purpose of simplification, there are still uncertainties in the physical phenomena of the gas-liquid flow on the surface of the ship hull [13,14].

Previous thermo-technical analysis of heat transfer processes of SHHE with gas-liquid flows has showed that key influential parameters for the processes are specific air consumption per air manifold, the temperature difference between the seawater heat transfer surface and the outboard water, properties of the cooling medium and the slope angle of the heat transfer surface. In order to specify the characteristics of the processes, preliminary visual observation and thermal engineering studies were carried out, which has confirmed the crucial impact of these factors.

Due to the lack of established relationships among the parameters in closed cooling systems, an experimental study was chosen to observe and to consider the impact of the parameters on the performance of the closed-loop cooling system of the power plant.
3. Experimental test rig

Fig. 5 shows the experimental setup for visual investigation of interaction between air bubbles and liquid, where section 4 is the SHHE model, section 1 is a transparent container with the dimensions of 1.0 x 0.5 x 0.1 m.

![Experimental Setup Diagram](image)

**Figure 5.** An experimental setup for visual investigation.

Air is supplied to the bottles (section 3) by the compressor (section 5). The valve (section 2) controls the flow rate of the air supplied to the manifold (section 6). The container is filled with fresh water doped with aluminum powder and ink. The experimental setup allows the study of movement as a single bubble and the gas-liquid flows along the inclined surface. The definition of specific air consumption used in this study is the air volumetric consumption divided by the length of air manifold.

Fig. 6 presents the experiment model with a labyrinth channel (section 2) with a dimension of 0.8 m in height and 0.5 m in width. The thickness of the dividing wall is 5 mm. In order to ensure minimal heat loss, the non-wet sides of the model were insulated. The power unit to be cooled is a 50 kW electric heater, as shown in Fig. 8. Fresh water was circulated in the system. Fresh water was heated up to a temperature of 85 °C. The water temperature is set to represent the cooling water temperature of the power plant. The model of SHHE (section 5) was placed inside a tank of 17 m$^3$ (section 4) filled with fresh water. The upper edge of the SHHE model is 0.5 m under the water surface, the lower edge of the SHHE is 1.0 m above the bottom of the tank. This arrangement is to ensure a minimal influence of the tank walls on the circulation of water. The dimensions of the test model were designed based on similarity analysis with the real system as shown in Fig. 4. All parameters of the system were set closely to the operational conditions of the real system. As a result, heat transfer from the SHHE to the outboard water was simulated for the case ship with a closed-loop cooling system in still water.

The average temperature of the outer surface of the heat transfer wall (section 5) was measured by six chromel-copel thermocouples placed on the surface of the heat exchanger with an equal space as shown in Fig. 6. The ambient temperature was measured by thermometers with a grade of 0.1 °C. In order to achieve stabilized temperatures of components and the system, the intervals between experimentations were 12 – 18 hours.
Figure 6. The ship hull heat exchanger model with labyrinth channels.

In the experiment, the variations of the system operation parameters were set with the following ranges:

- the temperature of fresh water in the heat exchanger model is 27 – 85 °C;
- the temperature of the water tank varies from 12 – 37 °C;
- the slope angle of the heat exchanger model is changed from 0° to – 85°;
- the specific flow rate of air is \( W_{GL} \times 2.9 \times 10^{-5} – 5.20 \times 10^{-3} \text{ m}^2/\text{s} \).

From the previous study (Fedorovsky, 1991), the system has the highest heat transfer effectiveness when the flow velocity in the labyrinth channel is 0.2 – 0.3 m/s, which is corresponding to the flow rate of fresh water in the heat exchanger model at 0.0004 – 0.0006 m\(^3\)/s.

The relative error of the heat transfer coefficient was determined as a square root of the relative error sum of defining parameters values. The relative error of the heat transfer coefficient is 6.78 %.

4. Results and discussion

It is well known [6] that reducing the thickness or creating a turbulence of the boundary layer improves the efficiency of the heat transfer. Therefore, the interaction of air bubbles with the SHHE surface disturbs the surface boundary layers, facilitating and improving heat dissipation. The enhancement in the heat transfer achieved by transverse pulsations of rising air bubbles and turbulence of the boundary layer has been observed and measured.

A bubble with a diameter of 5 mm at \( \phi = 0° \) has a rising velocity of 0.33 m/s, and it is 0.2 m/s at \( \phi = – 65° \), which is more than 1.6 times less than at \( \phi = 0° \). This indicates that the air bubble rising velocity is grown up as the angle of the slope is increased. In the meantime, the experiment results also show that the rising velocity of air bubbles grows up as the bubble size increases. For example, at \( \phi = – 30° \) with the bubble diameter of 3 mm, rising velocity is 0.2 m/s, whereas, it is 0.32 m/s when the bubble diameter is 8 mm.

The conclusion is that a rising bubble initiates movement of the surrounding water with a velocity of 0.1 to 0.15 m/s, which is less than that of the bubble [4]. This conclusion is in consistence with the results observed in this experiment.

The development of the bubble’s transverse interaction with surrounding water can be clearly observed as the bubble’s diameter increases from 3 mm to 10 mm. The interaction disturbs the boundary layer’s flow, leading to an increment in the heat transfer coefficient. It is also observed that the movement along surface bubbles produces a scraping effect. The scraping effect also enhances the
heat transfer coefficient.

5. Conclusion
A floating nuclear power plant is a promising solution to secure energy supply for remote areas. In compliance with the performance requirements of classification societies as well as requirements of the International Atomic Energy Agency and concerning the potential radioactive pollution, the use of open-loop cooling systems is environmentally unsafe. The solution proposed in this paper is that applying the closed-loop cooling system with SHHE for the floating nuclear power plant avoids the utilization of seaside dirty and fouled water and reduces the risk of radioactive emission. The results presented in the paper prove that the gas-liquid flow improves the performance of the closed-loop cooling system. The maximum heat transfer coefficient for combined free convection and the gas-liquid flow can be achieved by setting the surface slope angle of the SHHE at about $\phi = -30^\circ$ with the specific air flow rate at $0.3 \cdot 10^{-3} - 4 \cdot 10^{-3} \text{ m}^2/\text{s}$.

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