Design of A Model of Liquid Feeder to an Incinerator of Hazardous Waste and its Optimization from the Cooling Point of View: Part I

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Abstract— *A series of articles aimed at the cooling of the liquid radioactive waste feeder into the incinerator space optimization. The first part of the article offers a theoretical analysis of radioactive waste and the possibilities of its incineration. It also deals with the heat transfer within the waste feeder by means of the criterion equations for the transverse flow around the pipe at an angle, thanks to which the required mass flow of the cooling medium is determined.*

Keywords*— *Hazardous Waste, Radioactive Waste, Heat Transfer, Cooling Optimization.

I. INTRODUCTION

A significant amount of waste is produced in the energy industry. These wastes are divided into several types according to the possibility of their further processing. For example, common waste can be recovered for energy or stored, and hazardous waste must be disposed of. A specific branch of the energy industry is nuclear energy. Radioactive waste is generated during the operation of a nuclear power plant. Safe storage of this waste is spatially and financially demanding. For this reason, volume reduction of radioactive waste is necessary before its further processing.

Some types of radioactive waste can be burned in an incinerator to minimize its volume. The resulting radioactive ash is then safely stored for a long time. The incinerator is equipped with a dowtherm and ionex feeder. It is necessary to effectively cool this feeder to maintain the limited working temperature of the ionex and thereby ensure problem-free operation.

II. TYPES OF RADIOACTIVE WASTE ACCORDING TO RADIOACTIVITY

Radioactive waste is generated not only during the operation of nuclear power plants, but also, for example, within medical and research facilities, in agriculture and in services. In general, the term radioactive waste refers to waste materials that, due to the high content of radionuclides, or due to irremovable contamination, cannot be further used, recycled and released into the environment. Radioactive waste can be divided into many categories based on their chemical, physical and radiochemical properties. The most common division of these wastes is based on their level of radioactivity and state. According to the degree of radioactivity, waste can be divided into low-level waste, intermediate-level waste and high-level waste.

Low-level waste contains a significant amount of only short-lived radionuclides. Their decomposition to a sufficiently low level usually takes only a few decades. Low-level waste includes waste consisting of various materials and states. These are, for example, parts of protective equipment for nuclear power plant workers, such as gloves and coats. Low-level waste makes up approximately 90% of total radioactive waste. A large part of this waste can be classified as combustible waste, which makes it possible to reduce the total volume of waste to a large extent.

Intermediate-level waste contains significant quantities of long-lived radionuclides which do not generate significant decay heat. These are wastes from industrial facilities and institutional radioactive wastes, which, after reducing their volume, can be further stored in a multi-barrier protection system, or safely disposed of.

High-level waste consists of α-emitters and waste arising from fission products of uranium fuel in the reactor. Most high-level waste results from the reprocessing of spent nuclear fuel. If the nuclear reactor fuel that has been removed from a reactor following irradiation is treated as a waste, it is also considered a type of high-level waste. This type of radioactive waste is characterized by a high level of radioactivity and also radiotoxicity. Spent nuclear fuel contains more than 1000 radionuclides. It is essential to prevent these nuclides from entering the environment for an extremely long period of thousands of years. In order to achieve a decrease in the radioactivity and thermal output of high-level waste, it is necessary to cool the fuel for a period of 3 to 5 years. Subsequently, the cooled fuel can be moved and stored for up to 50 years in spent fuel interim storage. After the decrease in radioactivity and residual heat output, it is possible to definitively store the waste in a deep repository.

III. TYPES OF RADIOACTIVE WASTE ACCORDING TO STATE

According to its state, radioactive waste is divided into solid, liquid and gaseous. Solid radioactive waste can be created in two ways. The first is activation by the direct influence of radioactive radiation, when solid materials themselves become emitters. The second way is the contamination of solid materials in contact with active media, for example with the cooling medium of the primary circuit. Some contaminated components and equipment, such as primary circuit piping, can continue to operate. Other equipment and tools that may come into contact, for example, with power plant workers, must be decontaminated. Some contaminated materials, such as various filters, measuring devices, laboratory aids and others, are no longer usable due to their high activity. Contaminated elements of the building structure of the power plant are specific radioactive waste. It must be disposed of only when the power plant is decommissioned.

The liquid wastes generated during the operation of the nuclear power plant have different chemical composition and activity. In terms of volume, they usually represent the largest part of the nuclear power plant's radioactive waste. Some liquid wastes can be discharged outside the premises of the nuclear power plant after decontamination below the permissible level. Decontaminated wastewater with an activity above the permissible standard can be reused in the operation of a nuclear power plant after treatment by evaporation, ion exchange or chemical treatment. Such waters include, for example, wastewater from laundries and drainage water from pipe systems and equipment.

During the processing of reusable radioactive liquid waste, non-reusable wastewater is produced as secondary waste. Sometimes this waste is referred to as semi-liquid. These are concentrates and sludges that cannot be discharged from the power plant premises, while the majority of them are low-level and intermediate-level waste. A small part is made up of highly active concentrated residues. Before placing this type of waste in a deep repository, it is necessary to modify its form through various processes, such as cementation, bituminization and vitrification).

A relatively large part of the waste produced in the nuclear power plant consists of gaseous radioactive waste. It is discharged from the ventilation chimney after treatment and monitoring. Its quantity and composition are primarily determined by the activity from the exhaust systems of technological equipment and operating rooms. Due to the short half-life of the contained radionuclides and relatively low biological efficiency compared to other types of waste, gaseous radioactive wastes represent a minor technological problem in their treatment and processing.

IV. INCINERATION OF RADIOACTIVE WASTE

Depending on the type and properties of radioactive waste, there are several technological processes for its effective disposal. These processes include, for example, bituminization, vitrification and incineration. During the incineration process, combustible solid and liquid radioactive waste is disposed of. Incineration is not a waste-free technology. The primary goal of incinerating radioactive waste is to reduce its volume.

The diagram of the low-level waste treatment process using incineration is shown in fig. 1. After initial sorting, solid radioactive waste is brought in barrels for further sorting. After weighing and measuring the activity of radionuclides, compactable solid waste is compacted through a high-pressure press in barrels, which are then stored in fiber concrete containers. Combustible wastes are brought to the premises of the incinerator using transport devices designed for this purpose in gradually dosed quantities. In addition to solid fuel, liquid radioactive waste with oil is dosed into the incinerator to support combustion along with ionex.

Incineration takes place in the main incineration furnace at temperatures in the range of 750-950 °C. The generated radioactive gases are combusted in the combustion chamber at a temperature of 1000 °C. After cooling, the remaining gases are cleaned and filtered in special equipment. The ash produced by combustion has different grain sizes and compositions. It is fixed in the strengthening matrix by adding paraffin. The spent water used for flue gas cleaning is after treatment used for the preparation of cement grout.

The cementation device enables treatment of solid radioactive wastes, or of radioactive wastes fixed in the matrix, with a cement grout mixed with concentrates, sludge and saturated sorbents into a fiber concrete container, which is sealed after filling and stored in the dispatch warehouse for a specified period of time for aging.

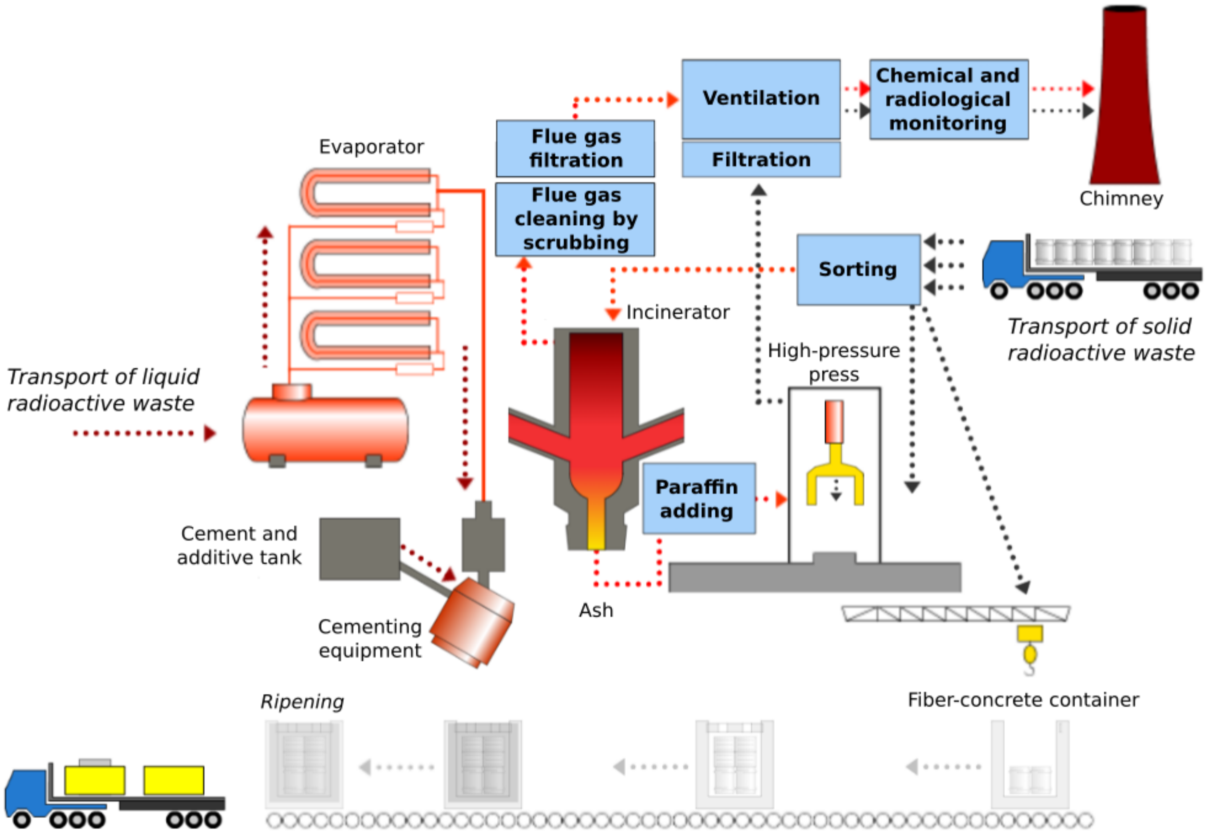

FIGURE 1: Diagram of the low-level waste treatment process

V. DETERMINATION OF THE MASS FLOW OF COOLING WATER

An important role in the incineration process has the feeder of liquid radioactive waste with ionex, which brings them into the premises of the main incinerator (Fig. 2). To support combustion, heating gas is supplied together with liquid waste. Foam serves as a transport medium for ionex.

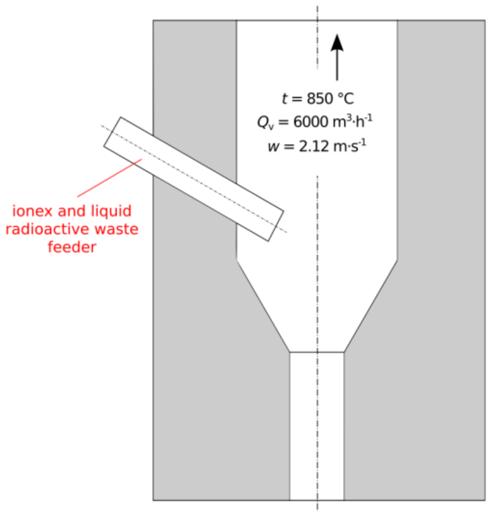

FIGURE 2: Location of the feeder in the incinerator premises

Ionex has a certain range of working temperatures, and when the maximum temperature is exceeded, ionex is baked on the walls of the feeder pipe. This ultimately disrupts the continuity of the combustion process. It is therefore necessary to avoid exceeding the maximum permitted temperature by effective cooling.

When determining the properties of the flue gas using the software, the theoretical composition of the flue gas of the waste mixture was used (Table 1).

TABLE 1
THEORETICAL COMPOSITION OF THE FLUE GAS OF THE WASTE MIXTURE

O_{2min} ($m^3 \cdot kg^{-1}$)	29.3813	O_{2min} ($\% \cdot kg^{-1}$)	12.1853
V_{CO2} ($m^3 \cdot kg^{-1}$)	21.9667	V_{CO2} ($\% \cdot kg^{-1}$)	9.1103
V_{SO2} ($m^3 \cdot kg^{-1}$)	0.04885	V_{SO2} ($\% \cdot kg^{-1}$)	0.0203
V_{H2O} ($m^3 \cdot kg^{-1}$)	14.5678	V_{H2O} ($\% \cdot kg^{-1}$)	6.0417
V_{N2} ($m^3 \cdot kg^{-1}$)	177.8494	V_{N2} ($\% \cdot kg^{-1}$)	73.7594
V_{O2} ($m^3 \cdot kg^{-1}$)	26.688	V_{O2} ($\% \cdot kg^{-1}$)	11.0683

Based on the data from Table 1, the properties of the flue gas (Table 2) necessary for further calculations were determined.

TABLE 2
PROPERTIES OF THE FLUE GAS OF THE WASTE MIXTURE

Kinematic viscosity ν ($m^2 \cdot s^{-1}$)	$74.14562 \cdot 10^{-6}$
Dynamic viscosity η (Pa·s)	34.29172
Density ρ ($kg \cdot m^{-3}$)	0.46249
Prandtl criterion *Pr*	0.7097

The calculation of the heat transfer coefficient α was carried out using the criterion equations for the transverse flow around the pipe at an angle. To calculate the Reynolds criterion *Re*, it was necessary to determine the characteristic dimension *l*:

$$l = \frac{\pi \cdot d}{2} = \frac{\pi}{2} \cdot 0.202 = 0.317 \text{ (m)} \tag{1}$$

Where *d* is the outer diameter of the pipe (m).

Then the following equation is used to calculate *Re*:

$$Re = \frac{\omega \cdot l}{\nu} = \frac{2.12 \cdot 0.317}{74.14562 \cdot 10^{-6}} = 9063.79 \tag{2}$$

Where ω is the fluid velocity ($m \cdot s^{-1}$), l is the characteristic dimension (m) and ν is the kinematic viscosity ($m^2 \cdot s^{-1}$).

The calculation of the Nusselt criterion *Nu* is expressed by equations 3 – 8:

$$Nu_{\mathrm{l,lam}} = 0.664 \cdot \sqrt{Re} \cdot \sqrt[3]{Pr} = 0.664 \cdot \sqrt{9063.79} \cdot \sqrt[3]{0.7097} = 56.387 \tag{3}$$

$$Nu_{\mathrm{l,turb}} = \frac{0.037 \cdot Re^{0.8} \cdot Pr}{1 + 2.443 \cdot Re^{-0.1} \cdot (Pr^{\frac{2}{3}} - 1)} = \frac{0.037 \cdot 9063.79^{0.8} \cdot 0.7097}{1 + 2.443 \cdot 9063.79^{-0.1} \cdot (0.7097^{\frac{2}{3}} - 1)} = 48.131 \tag{4}$$

$$Nu_{\mathrm{l,0}} = 0.3 + \sqrt{Nu_{\mathrm{l,lam}}^2 + Nu_{\mathrm{l,turb}}^2} = 0.3 + \sqrt{56.387^2 + 48.131^2} = 74.436 \tag{5}$$

$$K = \left(\frac{T_{\mathrm{b}}}{T_{\mathrm{w}}}\right)^{0.12} = \left(\frac{\frac{1123.15 + 323.15}{2}}{323.15}\right)^{0.12} = 1.101 \tag{6}$$

Where T_b is the boundary layer temperature (K) a T_w is the wall temperature (K).

$$Nu_{\mathrm{l}} = Nu_{\mathrm{l,0}} \cdot K = 74.436 \cdot 1.101 = 81.954 \tag{7}$$

During flow around the pipe, we consider the angle of impact of the flue gases on the feeder to be 45°. The ratio $Nu_{\mathrm{l,\varphi}}/Nu_{\mathrm{l}}$ = 0.805 corresponds to this angle.

$$Nu_{\mathrm{l,\varphi}} = 0.805 \cdot Nu_{\mathrm{l}} = 0.805 \cdot 81.954 = 65.973 \tag{8}$$

Then equations 9 – 12 apply to the calculation of the convective, radiation and overall heat transfer coefficient:

$$S = \pi \frac{d^2}{2} + \pi \cdot d \cdot L = \pi \frac{0.202^2}{2} + \pi \cdot 0.202 \cdot 1.56 = 1.054\ (\mathrm{m}) \tag{9}$$

$$\alpha_{\mathrm{c}} = \frac{Nu_{\mathrm{l,\varphi}} \cdot \lambda}{l} = \frac{65.973 \cdot 0.069}{0.317} = 14.36\ (\mathrm{W} \cdot \mathrm{m}^{-2} \cdot \mathrm{K}^{-1}) \tag{10}$$

$$\alpha_{\mathrm{r}} = \frac{\varepsilon \cdot \sigma \cdot S\ (T_{\mathrm{a}}^4 - T_{\mathrm{m}}^4)}{S\ (T_{\mathrm{a}} - T_{\mathrm{m}})} = \frac{0.9 \cdot 5.6704 \cdot 10^{-8} \cdot 1.054 \cdot (1123.15^4 - 323.15^4)}{1.054 \cdot (1123.15 - 323.15)} = 100.82\ (W \cdot m^{-2} \cdot K^{-1}) \tag{11}$$

$$\alpha_{\mathrm{o}} = \alpha_{\mathrm{c}} + \alpha_{\mathrm{r}} = 14.36 + 100.82 = 115.18\ (W \cdot m^{-2} \cdot K^{-1}) \tag{12}$$

where S is the surface of the body (m^2), L is the pipe length (m), α_{c} is the convective heat transfer coefficient (W·m^{-2}·K^{-1}), α_{r} is the radiation heat transfer coefficient (W·m^{-2}·K^{-1}), α_{o} is the overall heat transfer (W·m^{-2}·K^{-1}), λ is the thermal conductivity coefficient (W·m^{-1}·K^{-1}), ε is the body emissivity (-), σ is the Stefan–Boltzmann constant (W·m^{-2}·K^{-4}), T_{a} the ambient temperature (K) and T_{m} is the medium temperature inside the body (K).

After determining the convection and radiation coefficient of heat transfer, it is possible to determine the heat flow by convection P_{k} and radiation P_{s}:

$$P_{\mathrm{c}} = \alpha_{\mathrm{c}} \cdot S\ (T_{\mathrm{a}} - T_{\mathrm{m}}) = 14.36 \cdot 1.054 \cdot (1123.15 - 323.15) = 12\,108.3\ (W) \tag{13}$$

$$P_{\mathrm{r}} = \varepsilon \cdot \sigma \cdot S\ (T_{\mathrm{a}}^4 - T_{\mathrm{m}}^4) = 0.9 \cdot 5.6704 \cdot 10^{-8} \cdot 1.054 \cdot (1123.15^4 - 323.15^4) = 85\,594.8\ (W) \tag{14}$$

The last step after the calculation of the total heat flow by radiation and convection is the determination of the mass flow of water Q_{m} required for effective cooling of the feeder. Treated river water with an average temperature of 20 °C serves as a coolant.

$$Q_{\mathrm{m}} = \frac{P_{\mathrm{c}} + P_{\mathrm{r}}}{c_{\mathrm{p,H2O}}\ (T_2 - T_1)} = \frac{12\,108.3 + 85\,594.8}{4180 \cdot (323.15 - 293.15)} = 0.779\ (\mathrm{kg} \cdot \mathrm{s}^{-1}) \tag{15}$$

Where $c_{\mathrm{p,H2O}}$ is the specific heat capacity of water (J·kg^{-1}·K^{-1}), T_1 is the water temperature at the entrance to the body (K) and T_2 is the water temperature at the outlet of the body (K).

VI. CONCLUSION

Although the positive benefits of nuclear energy for mankind are undeniable, for its safe operation, proper management of the waste generated during the production of electricity is essential. The disposal of radioactive waste is possible by various methods that are constantly being developed and made more efficient. Using the criterion equations, it is possible to determine the heat transfer coefficients and subsequently determine the heat flow by convection and radiation during the cooling process of the liquid radioactive waste feeder to the incinerator. Knowing the total heat flow is essential for the next steps in the process of optimizing the feeder cooling through numerical simulations, which will be covered in Part II. In the calculations, the worst possible scenario was considered, when the cooling water reaches up to 20 °C. When using cooling water at lower temperatures, it would be possible to consider a lower mass flow, which makes it possible to achieve financial savings in the area of treatment and transport of cooling water.

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