In this presented study, the cooling problem of the İ.T.Ü. Triga Mark-II reactor has been handled and analyzed, and solutions were proposed. First of all, a thermal model of the reactor, heat exchanger, and cooling tower trio was established in the reactor. With this model, which was obtained with the help of experimental data, the parameters affecting the change of reactor water temperature over time were determined, and significant findings were obtained by investigating the possibilities of increasing the cooling power of the existing system. Then, using these mathematical equations, the effects of parameters that can affect the power of the reactor cooling system are investigated. The parameters affecting the cooling power are the cooling water flow rates in the second cooling circuits and the deposited layer that may exist as a result of numerical calculations. Different models have been created with machine learning algorithms (page regression, decision tree) to estimate the effect of the deposit layer. The mathematical and predictive models obtained with the experimental data for the heat transfer coefficient of the deposit layer \( h_{db} \) were compared. The pace regression (PR) algorithm modeled the \( h_{db} \) values with the least error rate (RMSE: 1.66) among the models. It has been calculated that the average tank water temperature will decrease by approximately 3.5 °C if the deposits layer is cleared.

Key words: Triga Mark II; heat exchanger; deposit layer, heat transfer coefficient; machine learning algorithm; equation derivation

1. Introduction

Due to the properties of the fluid used in the heat exchangers, a deposits layer (i.e., lime, particles, residue) occurs on the heat exchanger surface over time. As a result of this situation, the thermal efficiency of the heat exchanger decreases, and accordingly, the fuel consumption increases. Many studies on different subjects related to the deposit layer formed in the heat exchangers are given in Table 1. In these studies, the system in which the depositional layer was examined and its effects were taken into account. The adverse effects of the deposition layer, which is a negative factor for heat exchangers, have been studied in detail.

Built for education and research purposes, the upper limit given for the average tank water temperature of the Triga Mark-II reactor is 43.1 °C [1,2]. However, due to the insufficient cooling system, the average tank water temperature at high powers rises above this given temperature limit,
especially in summer [3]. The tendency of the temperature to exceed the given upper limit values increases the humidity rate on and around the pool surface. For this reason, the risk of corrosion and failure in mechanical, electrical, and electronic systems increases, and the risk of corrosion increases in materials in contact with cooling water [1,2]. In addition, the resin of demineralizer in the tank water treatment system loses its properties rapidly due to high temperature and can eventually deteriorate completely [2].

In this presented study, the cooling problem of the nuclear reactor was analyzed within the scope of the problems mentioned in the previous paragraph. For this, first of all, in the Triga Mark-II reactor, the reactor-heat exchanger thermal model has been established [4]. With the help of this model and experimental data, variation of the reactor tank water temperature was determined. In order to construct the thermal model of the nuclear reactor cooling system, it has been assumed that the reactor operates at a specific constant power. Tank water temperature values were measured from 7 different points [5]. Mathematical equations that give the time-dependent variation of the cooling water, temperature values, and total heat transfer values in the reactor tank and heat exchanger, respectively, were solved with the Wolfram Mathematica software non-Linear fit model [4]. Then, using this mathematical model, the parameters that could affect the power of the reactor's cooling system were investigated. The extent to which changing the flow rates and clearing the deposit layer can improve the cooling power has been investigated. In addition, the deposit layer effect affecting the total heat transfer coefficient of the reactor cooling system and the reactor tank water temperature was estimated by the decision tree algorithm, a machine learning algorithm. The results of the predictive model obtained and the mathematical model obtained with the experimental data have been obtained pretty similar to each other.

2. Material and Methods

2.1. Triga Mark II Nuclear Research Reactor Cooling System

The cooling system of the Triga Mark II reactor examined in this study consists of two parts (Figure 1). These are a tube-enveloped cross-flow heat exchanger, and a cooling tower connected to the tube-enveloped cross-flow heat exchanger [1]. The geometric dimensions and manufacturing features of the heat exchanger were taken from the study of Akay and Das (2021) [4].

In the first cooling circuit, the reactor core is cooled as follows. The thermal energy produced in the fuel elements in the reactor core is drawn through the natural convection of water in the tank. The heated water rises towards the tank surface and is sent to the heat exchanger by being absorbed by the first circuit circulation pump 90 cm below the surface. By transferring the thermal energy drawn from the reactor core through the heat exchanger to the water circulating in the second cooling circuit, the cooled water returns to the reactor core to continue its cooling function. The heat exchanger working principal diagram is given in Figure 2. The heat exchanger is manufactured with a total of seven passes. Six of these passages are on the side of the first circuit of the cooling section, and one passage is on the side of the second circuit. Tube bundles in the heat exchanger connect both circuits with the body of the heat exchanger.

In Figure 2, the flow flowing from the inside of the heat exchanger (inside the pipe) is used in the first circuit of the cooling system, and the flow from the outside (shell) is used in the second circuit.
<table>
<thead>
<tr>
<th>The part in which the deposit layer was examined</th>
<th>Researched attribute</th>
<th>The effect of deposits</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tubes from the super heater of a lignite utility boiler</td>
<td>Heat transfer rate</td>
<td>A reduction of 8-17% in the heat transfer rate because of deposition</td>
<td>[6]</td>
</tr>
<tr>
<td>Compact Heat Exchanger</td>
<td>Effects of deposit particle size in the range of 1 μm to 4 mm on the pressure drop in the heat exchanger</td>
<td>Particle deposit increased the pressure drop of the heat exchanger.</td>
<td>[7]</td>
</tr>
<tr>
<td>The tube bundle heat exchanger</td>
<td>Effect of fuel gas velocity on relative deposition ratio</td>
<td>At the same fluid velocity, the relative deposition rate of particles with a diameter of 5 μm is greatest and that of particles with a diameter of 10 μm is the smallest.</td>
<td>[8]</td>
</tr>
<tr>
<td>Pressurized Water Reactor</td>
<td>Corrosion-Related Unidentified Deposit (CRUD)</td>
<td>Radial CRUD deposit layer is highest in the flow range between 7 m/s and 15 m/s. The deposit carried by the fluid and formed into the particles increased the electrokinetic effects occurring at high speeds.</td>
<td>[9]</td>
</tr>
<tr>
<td>Shell and tube heat exchanger in petroleum refineries</td>
<td>Asphaltenes Deposition</td>
<td>It was determined with the help of CFD simulation that the deposit layer of asphalt particles in the heat exchanger occurred in the back cover of the heat exchanger and in the lower pipe layer.</td>
<td>[10]</td>
</tr>
<tr>
<td>Rectangular heat exchanger channel</td>
<td>The deposition of gas-side fly ash particles on the heating surface</td>
<td>The ceiling and side walls of the heat exchanger have less deposition efficiency than the floor part.</td>
<td>[11]</td>
</tr>
<tr>
<td>The helium flow in intermediate heat exchanger</td>
<td>Graphite particle deposition on the deflector at the entrance passage of the intermediate heat exchanger</td>
<td>The particle deposition rate at the deflector inlet of the intermediate heat exchanger decreases first and then increases in the inlet path of the intermediate heat exchanger.</td>
<td>[12]</td>
</tr>
<tr>
<td>Surface of boilers</td>
<td>Ash particles deposition</td>
<td>Serbian coal slag values (lignitic-type-ash coals) showed a tendency to form deposits in boiler heating.</td>
<td>[13]</td>
</tr>
<tr>
<td>Plate-fin heat exchangers</td>
<td>Effect of deposits on fluid inlet velocity and temperature difference in plate heat exchangers</td>
<td>As the critical air velocity in the heat exchanger increases, the particle deposition rate decreases, and as the particle size increases, the deposition increases. The temperature difference increased the average deposition efficiency of 1μm particles and decreased the average deposition efficiency of 7μm particles.</td>
<td>[14]</td>
</tr>
<tr>
<td>Plate heat exchangers</td>
<td>Effect of deposit on heat exchanger inlet and outlet on thermal efficiency</td>
<td>The deposit reduces the efficiency of the heat exchangers and makes the cleaning process increasingly difficult.</td>
<td>[15]</td>
</tr>
<tr>
<td>The circular tube bundle heat exchanger</td>
<td>Investigation of the effects of longitudinal pipe spacing, transverse pipe spacing and pipe geometry on deposit formation</td>
<td>Elliptical tube bundles reduced deposit formation</td>
<td>[16]</td>
</tr>
</tbody>
</table>
This study investigated the effects of the deposit layer that the fluid can form in the pipe interior on heat transfer. The effects of deposits that may occur at different fluid flow rates in the pipe have been investigated. In Figure 3, the representation of the deposits layer that is likely to form in the pipe is given. The mass flow rate change of the fluid has been selected according to the allowable operating temperature range of the reactor [1].
The reactor heat exchanger design features used in the calculations are given in Table 2. In this table, detailed specifications of one of the reactor and the second cooling circuits are given.

**Table 2. Basic design features and geometric dimensions of the reactor heat exchanger [1,2]**

<table>
<thead>
<tr>
<th>Design Features</th>
<th>First Cooling Circuit</th>
<th>Second Cooling Circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow rate</td>
<td>1.57 - 21.57 kg/s</td>
<td>5.5 - 15.5 kg/s</td>
</tr>
<tr>
<td>Inlet temperature</td>
<td>41.1 °C</td>
<td>26.7 °C</td>
</tr>
<tr>
<td>Outlet temperature</td>
<td>32.2 °C</td>
<td>32.2 °C</td>
</tr>
<tr>
<td>Operation pressure</td>
<td>7.95x10^5 Pa</td>
<td>7.95x10^5 Pa</td>
</tr>
<tr>
<td>Design temperature</td>
<td>150 °C</td>
<td>150 °C</td>
</tr>
<tr>
<td>Material</td>
<td>SS-304 stainless steel</td>
<td>Non-alloy steel</td>
</tr>
<tr>
<td>Total area</td>
<td>24.84 m² (inner surface)</td>
<td>31.78 m² (outer surface)</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>2.09x10⁻² m (pipe)</td>
<td>3.56x10⁻¹ m (Shell)</td>
</tr>
<tr>
<td>Outer diameter</td>
<td>2.67x10⁻² m (pipe)</td>
<td></td>
</tr>
<tr>
<td>Number of fluid passes</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>Number</td>
<td>112 pipes</td>
<td>1 shell</td>
</tr>
<tr>
<td>Flow cross-sectional area</td>
<td>6.51x10⁻³ m²</td>
<td>6.09x10⁻² m²</td>
</tr>
</tbody>
</table>

The flow chart expressing the research process headings of this presented computational study is given in Figure 4.

![Figure 4. The flow chart expressing the process of this work](image-url)
2.2. Determination of the heat transfer coefficients of the reactor cooling system

In the heat transfer coefficient calculations of the shell-tube-envelope heat exchangers, it is complicated to calculate the heat transfer coefficient of the heat exchanger because the flow inside the envelope is irregular and complex. The heat transfer values found in this type of heat exchanger theory cannot be expected to be very close to the actual values. The immeasurable dimensions of the envelope curtains in the heat exchanger and the complexity of the fluid regime increase error of calculation heat transfer of the heat exchanger [17]. In addition to this, the deposit has probably formed on the outer surface of the pipes of the heat exchanger since no maintenance has been done to the interior for a long time and the water lost in the circuit is supplied directly from the city network as a result of the malfunctioning of the softener units. This situation is another factor that can increase the uncertainty of the result to be obtained with theoretical calculations.

For the reasons mentioned above, the heat exchangers’ total heat transfer coefficient values should be calculated based on experimental data. In this study, temperature data taken from seven different points was used when the reactor in the experimental study for the Traiga Mark II nuclear research reactor was operating with 200 kW power [17]. Equation 1 expression is fitted to these data using the least-squares method (adapted) [5]. As a result of this fit process, the tank water weight coefficient and the total heat transfer coefficient and its components, the heat transfer coefficients, and the heat transfer coefficient of a possible deposit, were found. In order for the fit process to converge more healthily and faster, the convection coefficients, which can be calculated in order, were calculated theoretically and used as the initial value data.

\[
T_k(t) = (1-a) \left[ T_{ke} + \frac{(1-\varepsilon)P_k}{\dot{m}_1 c_p \varepsilon} \left[ 1 - \exp \left( \frac{\dot{m}_1 c_p \varepsilon}{C_p [1-\varepsilon(1-a)]} (t_i-t) \right) \right] \right] + a \left[ T_{ke} + \frac{P_k}{\dot{m}_1 c_p \varepsilon} \left[ 1 - \exp \left( \frac{\dot{m}_1 c_p \varepsilon}{C_p [1-\varepsilon(1-a)]} (t_i-t) \right) \right] \right]
\]

(1)

Equation 1 is derived from Equations 2 and 3, which expresses the variation of reactor inlet and outlet temperatures over time in Akay and Das’s work [4]. Akay determined the inlet temperature of the reactor according to the energy balance between the cooling system and the reactor. Then he expressed the second circuit inlet temperature of the cooling system with Equation 4 [2].

\[
T_{rk}(t) = T_{ke} + \frac{(1-\varepsilon)P_k}{\dot{m}_1 c_p \varepsilon} \left[ 1 - \exp \left( \frac{\dot{m}_1 c_p \varepsilon}{C_p [1-\varepsilon(1-a)]} (t_i-t) \right) \right]
\]

(2)

\[
T_{ro}(t) = T_{ke} + \frac{P_k}{\dot{m}_1 c_p \varepsilon} \left[ 1 - \exp \left( \frac{\dot{m}_1 c_p \varepsilon}{C_p [1-\varepsilon(1-a)]} (t_i-t) \right) \right]
\]

(3)

\[
\dot{m}_1 c_p \left[ T_{ro}(t) - T_{rk}(t) \right] = \dot{m}_2 c_p \left[ T_{ke}(t) - T_{rk}(t) \right]
\]

(4)

If Equations 2 and 3 are arranged according to Equation 4, Equation 5, which gives the cooling tower inlet water temperature variation with time, is obtained. Thus, the average temperature of the reactor tank water can be calculated with Equation 1, and the cooling tower inlet water temperature can be calculated with Equation 5 [2].

\[
T_{kg}(t) = \frac{\dot{m}_1}{\dot{m}_2} \left[ T_{ke} + \frac{P_k}{\dot{m}_1 c_p \varepsilon} \left[ 1 - e^{\left( \frac{\dot{m}_1 c_p \varepsilon}{C_p [1-\varepsilon(1-a)]} (t_i-t) \right)} \right] \right] - \left[ T_{ke} + \frac{(1-\varepsilon)P_k}{\dot{m}_1 c_p \varepsilon} \left[ 1 - e^{\left( \frac{\dot{m}_1 c_p \varepsilon}{C_p [1-\varepsilon(1-a)]} (t_i-t) \right)} \right] \right] + T_{ke}
\]

(5)
2.3 Determination of deposit effect in reactor cooling system

In this chapter; the heat transfer coefficient of the second circuit side, the heat transfer coefficient of the deposit on the pipes of the heat exchanger, and the average tank water temperature weight coefficient \( a \), which relates the average tank water temperature with the inlet and outlet temperatures, have been determined with the help of curve fitting to the experimental data. The expression to be subjected to curve fitting is Equation 1, which gives the average tank water temperature variation over time. Equation 1 depends on the parameter \( \varepsilon \) and the weight coefficient \( a \). The \( \varepsilon \) parameter has been expressed in Equation 7 [18] in terms of NTU and R in Equation 6 expression [19].

\[
NTU = \frac{1}{\sqrt{1 + R^2}} \ln \left[ \frac{2 - (1 + R - \sqrt{1 + R^2})\varepsilon}{2 - (1 + R + \sqrt{1 + R^2})\varepsilon} \right]
\]

(6)

\[
\varepsilon = \frac{2\left[1 - e^{NTU(\sqrt{1 + R^2} - 1)}\right]}{1 + R - \sqrt{1 + R^2} - (1 + R + \sqrt{1 + R^2})e^{NTU(\sqrt{1 + R^2} - 1)}}
\]

(7)

The \( R \) parameter is found by dividing the first circuit mass flow value by the second circuit mass flow value. However, in order to know the NTU, it is necessary to know the total heat transfer coefficient \( U \) of the heat exchanger. \( U \) depends on knowing the heat transfer coefficients on the first-second circuit side of the heat exchanger and the heat transfer coefficient of the possible deposit layer. Since the flow geometry is smooth on the first circuit side and it is a type of flow where many healthy correlations can be found, Equations 10-18, which were calculated theoretically and depended on, were used for the convection coefficient of this side [20]. Equations 8 and 9 [21] were used to determine the flow characteristics values of the first and second cooling cycles. Equation 7 was used to calculate \( \text{Re} \) values, and Equation 8 was used to calculate flow velocity values. The parameters obtained by Equations 8 and 9 were used in Equations 10-13.

\[
\text{Re} = \frac{VD}{\nu}
\]

(8)

\[
V = \frac{\dot{m}}{\rho_d A_k}
\]

(9)

\[
Nu = 0.023\text{Re}^{0.8}\text{Pr}^n
\]

(10)

\[
Nu = \frac{h D_p}{\lambda_s}
\]

(11)

In Equation 8, the value of \( n \) is 0.3. According to the average tank water temperature \( T_{Ak} \) value (36.5°C), \( \lambda_s \) value is 0.622 W/m°C, \( D_{hi} \) value for the first cooling circuit is 2.9x10^{-2} and Pr value is 4.728. Equations 12 and 13 are obtained when the Reynolds number is written as a function of \( \dot{m}_1 \) according to these values.

\[
\text{Re} = \frac{34243}{7.57} \dot{m}_1 = 4.52 \times 10^3 \dot{m}_1
\]

(12)

\[
Nu = 35.95 \dot{m}_1^{0.8}
\]

(13)

Using Equation 13 and Equation 11 [22], the heat transfer coefficient of the first circuit side of the heat exchanger \( (h_1) \) is expressed by Equation 14 according to the \( \dot{m}_1 \) value.

\[
h_1 = \frac{\dot{m}_1^{0.8}}{9.35 \times 10^{-4}}
\]

(14)

In order to determine the heat transfer coefficient \( (h_2) \) of the second cooling circuit side of the heat exchanger, the same procedure was followed for the first circuit. Average values of reactor second cooling circuit water design temperatures are used for kinematic viscosity and Prandtl number. Calculations were made by taking the kinematic viscosity \( (\nu) \) value of 0.801x10^{-6} m²/s and the Pr value of 5.43 according to the average water temperature of 29.45°C for the second cooling circuit.
The shell of the second circuit of the heat exchanger are made of non-alloy steel, and the $D_{bd}$ value is $1.39 \times 10^{-2}$ m. In addition, the thermal conductivity coefficient ($\lambda_w$) is 16.3 W/m°C for the same average water temperature of 29.45°C [17].

The Reynolds number can be calculated by Equation 15 according to the number $m_2$.

$$Re = \frac{5258}{11.1} m_2 = 4.7 \times 10^2 m_2$$

The heat transfer coefficient ($h_2$) of the second circuit of the heat exchanger was calculated with Equation 17 obtained by using Equation 10 and 11.

$$h_2 = \frac{\dot{m}_2^{0.8}}{4.27 \times 10^{-3}}$$

The total heat transfer coefficient ($U$), which is defined according to the second circuit surface area in the heat exchangers, is expressed by Equation 18.

$$U = \frac{1}{h_2 + \frac{1}{\frac{(D_{bd} - D_{bi})}{2\lambda_w} D_{bd} + \frac{D_{bd}}{h_{bi} D_{bi}} + \frac{D_{bd}}{h_{bi} D_{bi}}}}$$

$h_{bi}$ and $h_{bd}$ are the heat convection coefficients of the deposits that may occur in the pipe's inner (first circuit) and outer (secondary circuit) parts, respectively. $D_{Lm}$ is the logarithmic average of the pipe inner and outer diameters. Equation 19 was used in $D_{Lm}$ calculations [23].

$$D_{Lm} = \frac{D_{bd} - D_{bi}}{\ln \frac{D_{bd}}{D_{bi}}}$$

Since high purity water is used in the first circuit, it is assumed that there is no lime layer or deposit on the inner surfaces of the heat exchanger pipe. For this reason, it is expected that the deposit layer can only form on the outer surfaces of the tubes (shell) that come into contact with the second circuit water. Thus, the second circuit convection coefficient, the heat convection coefficient of the deposit, and the weight coefficient $a$ were chosen as unknowns. As a result, the total heat transfer coefficient during the fit process has been expressed by Equation 20 using Equations 14, 17, and 18.

$$U = \frac{1}{\frac{1}{h_{bd}} + \frac{4.27 \times 10^{-3}}{\dot{m}_2^{0.8}} + \frac{0.0267}{2 \times 16.3 \ln \left( \frac{0.0267}{0.0209} \right)} + \frac{0.0267 \times 9.35 \times 10^{-4}}{\dot{m}_1^{0.8}}}$$

Equation 21 is obtained as a result of editing the expression Equation 20.

$$U = \frac{1}{\frac{1}{h_{bd}} + \frac{0.00427}{\dot{m}_2^{0.8}} + 2.0059 \times 10^{-4} + \frac{0.0011937}{\dot{m}_1^{0.8}}}$$

Equation 22 has been obtained using values of 0.0011937 for the coefficient $c_1$ and 0.00427 for the coefficient $c_2$ and replacing $1/h_{bd}$ with $d$.

$$U = \frac{1}{d + \frac{c_2}{\dot{m}_2^{0.8}} + 2.0059 \times 10^{-4} + \frac{c_1}{\dot{m}_1^{0.8}}}$$

In Equation 22, parameter $d$ expresses the heat transfer coefficient of the deposit layer under reactor operating conditions. Different $c_1$ and $c_2$ values were obtained for each flow rate and heat transfer coefficient values were obtained by using these constant values.
2.4 Machine learning algorithm

Machine Learning is described as a paradigm of methods that makes various inferences from existing data using statistical and mathematical methods and makes predictions on the unknown with these inferences [24,25]. They are computer algorithms that model a given problem according to the data obtained from the environment of the problem [26,27]. In the present study, decision tree regression (M5P) and PR algorithms are used to model deposit heat transfer coefficient values. The input and output parameters used for the structure of the models in machine learning algorithms are given in Table 3.

A total of 425 data were used in the modeling of the heat transfer coefficient of the deposit, which causes negative effects in the cooling system. 125 data were used to test the model to be created in this data set, and 300 data were used to train it. Ten-Cross validation method was used for data validation. Cross-validation was a technique used in model selection to better predict the error of a test in a machine learning model [28,29]. The regression Learner tab in MATLAB 2018b software was used to model $h_{bd}$ data.

Table 3. Parameters in the dataset used for machine learning algorithms models

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Unit</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_2$</td>
<td>(kg/s)</td>
<td>5.5</td>
<td>15.5</td>
</tr>
<tr>
<td>$U$</td>
<td>W/m$^2\circ$C</td>
<td>374.16</td>
<td>604.7</td>
</tr>
<tr>
<td>$T_R$</td>
<td>$\circ$C</td>
<td>38.6</td>
<td>47.1</td>
</tr>
<tr>
<td>$T_{Ri}$</td>
<td>$\circ$C</td>
<td>32.2</td>
<td>38.2</td>
</tr>
<tr>
<td>$T_{Ro}$</td>
<td>$\circ$C</td>
<td>38.2</td>
<td>48.1</td>
</tr>
<tr>
<td>$Re_2$</td>
<td>-</td>
<td>2585</td>
<td>7285</td>
</tr>
<tr>
<td>$Nu_2$</td>
<td>-</td>
<td>17.6</td>
<td>40.3</td>
</tr>
<tr>
<td>$h_2$</td>
<td>W/m$^2\circ$C</td>
<td>915.9</td>
<td>2098.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output Parameter</th>
<th>Unit</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_{bd}$</td>
<td>W/m$^2\circ$C</td>
<td>374.16</td>
<td>604.7</td>
</tr>
</tbody>
</table>

Decision Tree

Decision trees (DT) used in data modeling are widely used in predictive model creation and classification. The DT algorithm uses decision mechanisms based on feature variables arranged in a tree-like structure for prediction and classification. [30]. The DT algorithm uses the M5P algorithm, an extended version of the M5 algorithm [31]. One of the main advantages of model trees is that they can efficiently process large datasets with multiple dimensions. The basic structure consists of three essential parts called a node, branch, and leaf [32]. Construction of the tree uses standard deviation reduction (SDR), which maximizes the expected error reduction at the node, and the SDR is expressed by Equation 23 [33].

$$SDR = sd(S) - \sum_{i} \frac{S_i}{|S|} \times sd(S_i)$$

(23)

$S$ is the set of data records reaching the node, $S_i$ is the clusters resulting from the node splitting according to a particular attribute, and $sd$ is the standard deviation [29].
Regression analysis is a widely used data analysis method in statistical analysis, and this method is a technique with both descriptive and predictive purposes [34].

PACE (Projection Adjustment by Contribution Estimation) regression algorithm is a new approach to fit linear models based on consideration of similar models [35]. Regression analysis is generally used to derive a linear model from a data set. It uses the predictive properties of ordinary little squares for the resulting model. The ordinary little squares method has a solid theory but lacks satisfactory accuracy. PR improves classical ordinary least squares regression by using cluster analysis to evaluate the impact of each variable, estimate their contribution to overall regressions, and develop the statistical basis [36].

Wang and Witten developed PR and showed that it performs best for high-dimensional data than other regression models [37]. Six different regression procedures, named PACE1 to PACE6, were developed, which share a common basic idea that estimated the distribution of the effects of variables from the data and used this to improve modeling. The first four procedures used OLS (ordinary least square) subset selection, including the OLS itself. PACE 5, on the other hand, was based on the empirical Bayes (EB) method [36]. As with other forms of linear regression, the PR, OLS, and EB methods used to model any parameter is a linear combination of features in Equation 24 format [36].

\[ \text{Modeled Parameter} = \alpha_1 A_1 + \alpha_2 B_1 + \alpha_3 C_1 + \alpha_4 D_1 + \alpha_5 E_1 + \ldots \]  

(24)

In Equation 18, expressions such as A, B, C, D, E were the input parameters in the mesh created for the modeled parameter. The \( \alpha_i \) values were the weight coefficients that affect the parameters obtained by the PR methods. It was important to note that the resulting model was a linear combination of features. In this way, a simplified forecasting model could be obtained, and the calculation time could be reduced.

**Error Analysis**

Root mean square error (RMSE) analysis is used to determine the accuracy of the models created by machine learning algorithms. The formula and parameters of the RMSE analysis are given in Table 4 [38].

**Table 4. Error Analysis and Formula**

<table>
<thead>
<tr>
<th>Error Analysis</th>
<th>Formulas</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMSE</td>
<td>( \sqrt{\frac{(P_1 - A_1)^2 + \ldots + (P_n - A_n)^2}{n}} )</td>
<td>n: Total Estimated Value</td>
</tr>
<tr>
<td></td>
<td></td>
<td>P: Predicted Value</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A: Actual Value</td>
</tr>
</tbody>
</table>

3. Result and Discussions

In this study, the effects of a deposit that may occur in the cooling system of the ITU Triga MARK II nuclear research reactor on the average reactor tank water (\( T_R \)) temperature values and the total heat transfer of the cooling system were investigated. The previously measured tank temperature data and cooling system flow values [3] were fitted for this research to produce the reactor tank temperature equation (Equation 1). Then, the reactor's overall heat transfer coefficient equation has been delivered (Equation 14), and the effects of a build-up layer that may occur in the second part of the cooling circuit have been revealed. In addition, mathematical equations expressing the heat transfer coefficient of the first layer that may occur in the system were produced using the PR algorithm. The results of the study are presented below under two headings as calculation and machine learning algorithms.
3.1. Calculation Procedure Results

The mass flow rate value in the second part of the heat exchanger used in the reactor cooling system and the temperature change of the reactor cooled by the heat exchanger with the deposit layer are shown in Figure 5. According to the reactor operating conditions, the reactor tank temperature range was chosen as 40-50 °C [1]. This figure has been added to better show the effect of cooling system mass flow changes on the operating temperature. The $T_R$ temperature value decreased to 13.25 kg/s flow rate and then increased exponentially. This situation indicates that the $\dot{m}_2$ mass flow rate should not be more than 13.25 kg/s flow rate.

In Figure 6, the variation of the residual heat transfer coefficient value that may occur in the second part of the heat exchanger according to the $\dot{m}_2$ mass flow value is shown. The heat transfer value of the deposit layer increased with the decrease of $\dot{m}_2$ flow rate. It can be accepted that the deposit, which is expected to cause poor heat transfer at low flow rates, will also reduce the heat transfer value of the reactor cooling system. Figure 7 shows the change in reactor tank temperature with increasing $\dot{m}_2$ flow rate. This temperature change was investigated according to the presence and absence of deposits in the cooling system heat exchanger. A low $T_R$ temperature value indicates that the reactor cooling system performs cooling with high heat transfer. According to Figure 7, in the case of deposits in the heat exchanger in the cooling system, the reactor temperature increases by an average of 3.5 °C. In addition, the $\dot{m}_2$ value being more than 13.25 kg/s causes the reactor tank temperature to increase.

![Graph](image)

**Figure 5.** Variation of TR values according to the mass flow rate in case of deposit

Figure 8 presents the variation of the total heat transfer value of the reactor cooling system concerning the deposit in the heat exchanger and the flow rate $\dot{m}_2$. In the absence of deposits, the total heat transfer value of the cooling system increases up to 13.25 kg/s $\dot{m}_2$ flow rate and decreases in subsequent flow values. In the case of deposits in the heat exchanger, the total heat transfer value of the cooling system shows a continuous decrease. According to Figure 8, the average heat transfer coefficient of the cooling system at all flow rates is 311.6 and 572.9 W/m²K, with and without deposits, respectively. The negative effect of the deposit that may form in the heat exchanger on the heat transfer of the reactor cooling system is seen in Figure 8.
Figure 6. Variation of the heat transfer coefficient of deposit with the mass flow rate value

Figure 7. Effect of $m_2$ mass flow rate increase on TR value with and without deposit layer

Figure 8. Change of U value with and without deposit layer according to $m_2$ value

3.2. Machine Learning Algorithms Results

This study used machine learning models to express the effects of deposits in the reactor cooling system on heat transfer. Mathematical equations describing the deposits heat transfer value were obtained using the PR algorithm. The M5P decision tree algorithm and PR algorithm were used to model the deposits heat transfer value.
In Figure 9, the tree structure created by the M5P decision tree for the $h_{bd}$ values model is seen. Decisions in the tree structure were determined according to $\dot{m}_2$ values, and $h_{bd}$ values were modeled according to the leaf equations of the tree formed as a result of these decisions. These equations are given in Table 5.

Table 6 shows the $h_{bd}$ mathematical equations obtained with OLS and EB in the PR algorithm. These equations obtained with the PR algorithm were determined according to the total heat transfer coefficient of the reactor cooling system, the cooling system’s second circuit heat transfer coefficient, the reactor tank cooling water inlet-outlet temperature, and the reactor tank temperature. These parameters were randomly selected from the input data by the PR algorithm.

![Figure 9. Decision tree structure of the M5P algorithm](image)

**Figure 9. Decision tree structure of the M5P algorithm**

### Table 5. Decision equations in the M5P decision tree

<table>
<thead>
<tr>
<th>Leaf Number (LM)</th>
<th>LM Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM num: 1</td>
<td>$h_{bd} = -27.4269 \cdot \dot{m}_2 + 746.9794$</td>
</tr>
<tr>
<td>LM num: 2</td>
<td>$h_{bd} = -31.3061 \cdot \dot{m}_2 + 791.4761$</td>
</tr>
<tr>
<td>LM num: 3</td>
<td>$h_{bd} = -57.5919 \cdot \dot{m}_2 + 1132.693$</td>
</tr>
<tr>
<td>LM num: 4</td>
<td>$h_{bd} = -62.8483 \cdot \dot{m}_2 + 1208.5806$</td>
</tr>
</tbody>
</table>

### Table 6. The deposits heat transfer value equations produced by the PR algorithms (OLS and EB)

<table>
<thead>
<tr>
<th>PR Models</th>
<th>Model Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLS</td>
<td>$h_{bd} = 2.9 \cdot U + (-0.3 \cdot h_2) + 0.5 \cdot T_{Ri} + 3.7 \cdot T_{Ro} + 32.2 \cdot T_{R} + (-14.4 \cdot Nu_2) -1785$</td>
</tr>
<tr>
<td>Empirical Bayes</td>
<td>$h_{bd} = 2.9 \cdot U + (-0.6 \cdot h_2) + 0.5 \cdot T_{Ri} + 3.7 \cdot T_{Ro} + 32.2 \cdot T_{R} + -1564$</td>
</tr>
</tbody>
</table>

Error analysis results of $h_{bd}$ models obtained by machine learning methods are given in Table 6. All methods modeled the deposits heat transfer value with less than 2% error.

Figure 10 shows the comparison of $h_{bd}$ values calculated with the help of Equation 16 using experimental data and $h_{bd}$ values modeled by machine learning algorithms. In addition, this figure presents the R (correlation coefficient) squared values of the machine learning algorithm models. According to the R squared value, the least faulty model is the model made with the PR algorithm EB method. As shown in Figure 10, the actual and estimated values are pretty close to each other.
4. Conclusions

In the present study, the total heat transfer coefficient of the heat exchanger, which is connected to the first and second sections of the cooling system of the research reactor, was determined. In the second cooling group, the heat transfer coefficient values of a deposit layer covering the pipes and causing an increase in the tank water temperature by worsening the heat transfer were calculated in detail. It has been determined that if the deposit layer covering the outer surface of the pipes in the heat exchanger is cleaned, the average tank water temperature will decrease by approximately 3.5°C. In addition, modeling was done with PR and M5P decision tree algorithms, which are machine learning algorithms, for the deposit layer calculated in the reactor cooling heat exchanger. The deposits heat transfer values obtained with the help of experimental data were modeled by the OLS, EB, and M5P algorithms with RMSE error values of 1.71, 1.66, and 1.99, respectively. A mathematical equation was derived by PR for the deposit layer that may occur in the cooling group of the TRIGA MARK-II nuclear research reactor. Thanks to these equations, more detailed information can be obtained about the deposits layer, which is difficult to determine in the reactor cooling group heat exchanger. With the help of the simple but effective mathematical equations derived with PR, deposit heat transfer effects can be observed in a heat exchanger simply by knowing the heat transfer and temperature values.

Nomenclature

- $a$: Weight coefficient
- $A_k$: Flow cross-sectional area ($m^2$)
- $c_p$: Specific heat capacity [kJ/kg K]
- $D_{bi}$: Pipe outer diameter [m]
- $D_{bd}$: Shell diameter [m]
- $D_{lm}$: Average logarithmic diameter [m]
- $\varepsilon$: Effectiveness of the heat exchanger
- $h_{bd}$: Deposit layer heat transfer coefficient [W/m²K]
- $h_1$: First cooling group heat transfer coefficient [W/m²K]
- $h_2$: Second cooling group heat transfer coefficient [W/m²K]
- $U$: Total heat transfer coefficient [W/m²K]
- $\lambda_s$: Thermal conductivity of steel [W/mK]
- $\lambda_w$: Thermal conductivity of water [W/mK]
he purificiation of bacterially infected I.T.U. corrosion products under –

3:100397.

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Hanzah JA, Nima MA. Experimental Study of Heat Transfer Enhancement in Double-Pipe Heat Exchanger

References


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