

Development of Web-Based Application for Analysis and Design of Steam Power Plant System Parameters Using Biomass Fuel

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ABSTRACT

The process of physically prototyping a power generation system is time consuming and costly. Adopting the concept of Digital Twin Technology offers a solution to improve the efficiency in prototyping processes. This study aims to develop a web-based application called ThePOCI for thermal analysis of steam power plant systems working with ideal Rankine cycle, and to evaluate the accuracy of the developed application. The ThePOCI thermal system application consisted of two main modules: Steam Power Plant Design and Combustion Analysis. Validation of the Combustion Analysis module revealed the largest calculation errors in the thermal-based model for variables including flue gas temperature (13.08%), temperature of boiler exit working fluid (16.93%), and turbine power (10.49%), yet all fall within the low error range. Validation of the Steam Power Plant Design module produced deviations of ideal and actual operating conditions of 2.22% and 0.88%, respectively, categorized as highly accurate. The validation results confirm that ThePOCI can accurately simulate the physical system of a steam power plant based on the ideal Rankine cycle. System emission calculations indicate potential for further research on the use of calliandra biomass in Organic Rankine Cycle (ORC)-based steam power plants, identified as the fuel producing the lowest emissions at 3,742.20 kgCO_{2e}/kW.

1. INTRODUCTION

The process of physically prototyping a power generation system requires a relative time consuming and costly. Research by [Hong & Lee, \(2018\)](#) found that the technical design of a steam power generation system is the most decisive factor in determining the amount of investment spent on physical construction. The physical construction of a power generation system is precarious financially due to limited knowledge regarding potential technical constraints of the system. The development of physical prototypes of power generation systems has the potential to reduce costs and increase the intensity of return on investment, but tends to be financially risky. The costs of physical prototyping increase initial capital, which can hinder the development of physical systems and reduce the rate of return on investment because physical prototypes cannot meet commercial requirements ([Lai & Locatelli, 2021a](#)). On the other hand, the continuously increasing demand for electricity and the requirement to provide low-emission electricity systems present technological, economic, and cost uncertainties ([Lai & Locatelli, 2021b](#)).

Adopting a Digital Twin Technology concept is offered as a solution to streamline prototyping time and costs. Digital Twin Technology accommodates the modeling and simulation of machine systems so that testing requirements are carried out before the physical construction stage ([Yildiz et al., 2020](#)). The Digital Twin Technology framework consists of physical, virtual, data, and control components. Virtual and data components play a role in system modeling and simulation, predictive performance analysis, and measurement data management ([Yassin et al., 2023](#)).

The development of the ThePOCI application aims to fulfill the role of virtual and data components of the Digital Twin Technology framework so that the costs and time required for physical prototype development can be optimized.

Previous studies have extensively utilized available applications such as Refprop, Epsilon Professional, and Cycle Tempo for power plant system analysis (Chen *et al.*, 2022; Hartulistiyoso *et al.*, 2020; Khankari & Karmakar, 2017). Additionally, previous studies have shown that the need for emission load analysis in power generation systems requires users to add models or install additional applications. The study by Tovar *et al.* (2024) added a life cycle analysis model to the MATLAB application to analyze emission loads in power generation systems. The study by Mayanti *et al.* (2021) also combined the Cycle Tempo and OpenLCA applications to analyze power plant systems and the resulting emission loads. Khankari & Karmakar, (2017) analyzed power plant systems using the Cycle Tempo application, but the emission load calculations were performed outside the application system. The applications mentioned above require users to install the application on their computers. This poses potential challenges in terms of accessibility and flexibility for users. Therefore, a thermal system application named ThePOCI was developed as a web-based application to enhance user accessibility and flexibility, allowing the application to be used without installing it on a computer (Kumar & Ram, 2023). Additionally, developing a web-based application enables the availability of a database system for storing, sharing, and retrieving data (Ozorhon *et al.*, 2014). The stored data is expected to be the foundation for developing a better system. The thermal system application developed also includes components for analyzing the emission load of steam power generation systems using life cycle climate performance (LCCP) approach, so users do not need to install additional applications to accommodate these needs. The LCCP approach is used in the ThePOCI application due to the potential use of refrigerants in steam power generation systems such as ORC systems. The International Institute of Refrigeration (IIR) has recommended using the LCCP method to analyze systems related to direct and indirect emissions from refrigerant use over their lifetime (IIR, 2015).

The research aims to develop a web-based thermal system application that enables thermal analysis of steam power plant systems, particularly those based on the Organic Rankine Cycle (ORC) based on the ideal Rankine cycle, evaluating the accuracy of the thermal system application in analyzing the specified planning parameters, including the ability to calculate system performance and emission loads using the LCCP method in steam power plants based on the ideal Rankine cycle. The research results in the form of the ThePOCI thermal system application are expected to be accessible to the public to assist academics, researchers, and industry in designing steam power plant systems.

2. MATERIALS AND METHODS

2.1. Tools and Materials

The research used hardware in the form of computers and physical models of Organic Rankine Cycle (ORC) systems, as well as software such as REFPROP for fluid thermal data provision, VS Code as a text editor, PHP for server-side programming, Apache for local server providers, Python for thermodynamic equation scripting and user backends, and MySQL for database management.

2.2. Experimental Setup

Data collection for validating of ThePOCI calculation of physical phenomena was carried out by testing the ORC physical model with the following setup in Figure 1. In the initial stage, a hopper supplied biomass fuel into the furnace. During the combustion process, three thermocouples were installed inside the furnace at the bottom, middle, and top to measure the combustion temperature. The flue gas flowed toward the furnace outlet, which was connected to a shell and spiral tube boiler. Thermocouples were installed on the furnace outlet and boiler outlet to measure the flue gas temperature before and after passing through the boiler. In the ORC system, the working fluid was pumped into the boiler with thermocouples and pressure transmitters installed on the pump outlet. The fluid received heat from the exhaust gas in the boiler, then flowed to the turbine for expansion and power generation. Temperature and pressure were measured at the boiler and turbine outlets before the fluid enters the condenser. The fluid exited the condenser with temperature and pressure measurements at the outlet before returning to the pump. All thermocouples and pressure transmitters were connected to the data acquisition system, which was then connected to a computer for data storage.

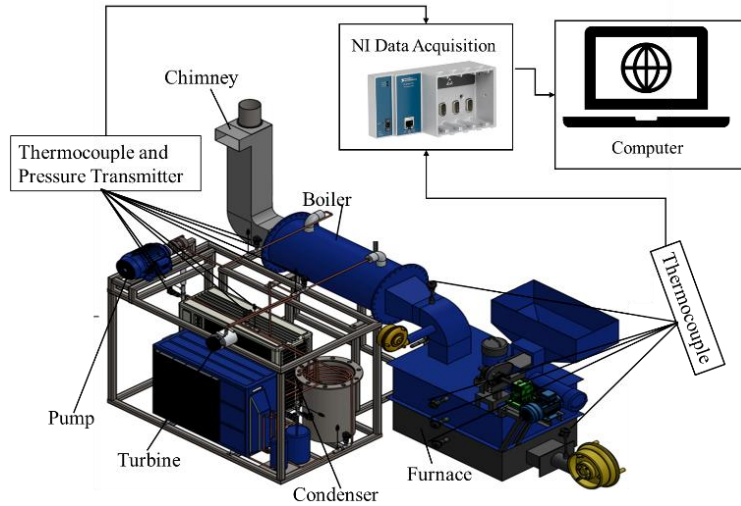


Figure 1. Experimental setup testing for biomass furnace integrated steam power plant

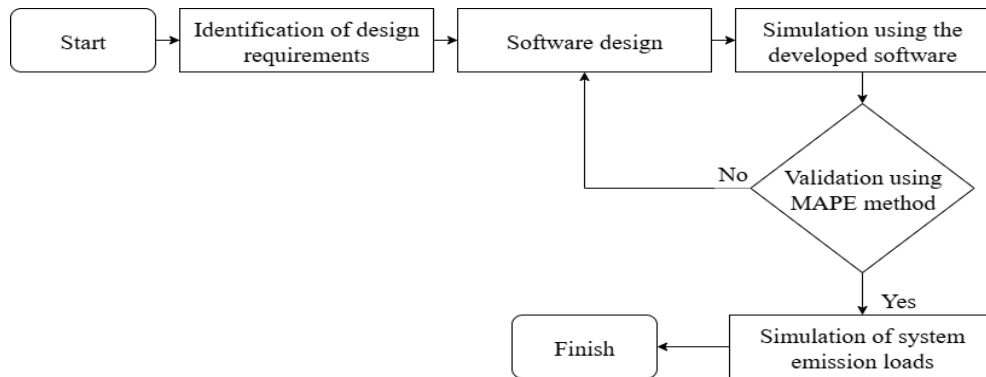


Figure 2. Research stage flowchart

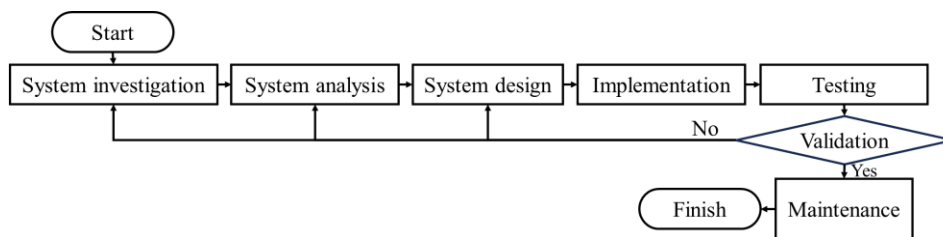


Figure 3. Software development flowchart using System Development Life Cycle (SDLC)

2.3. Stages of Research

The research consisted of several stages, which were presented in a flow chart in Figure 2. It shows the first step in designing ThePOCI application, which is identifying requirements focused on software and hardware requirements for application development. The thermal system application design stage follows the System Development Life Cycle (SDLC) method by O'Brien & Marakas (2010), which had been modified and presented in Figure 3. The system simulation phase was conducted after the ThePOCI application was fully developed using input data from a portion of the test results. The simulation results were validated against the test results. The research continued by calculating the system emissions after the validation results fell within the acceptable uncertainty category (MAPE < 20%).

2.4. Investigation and Analysis of the System

An investigation and analysis of the system was conducted regarding user requirements for the parameters presented on the application interface and the equations that compose the information. Steam power plant systems are divided into furnace components and steam power plant systems. Simulation calculations were performed in steady state. The equations for the boiler component refer to the principle of energy balance (Cengel & Boles, 2015), where the combustion input energy (\dot{Q}_{in}) is equal to the useful energy (\dot{Q}_g) or mathematically $\dot{Q}_{in} = \dot{Q}_g$. Further, input energy is the product of mass flow rate (\dot{m}_{fuel}) of biomass fuel per unit time (kg/s), and its calorific value (HHV) of fuel (kJ/kg), which was expressed by the following equation.

$$\dot{Q}_{in} = \dot{m}_{fuel} \times HHV \quad (1)$$

The combustion models developed by Boateng (2016) and Mawardi *et al.* (2024) were used in the ThePOCI application to calculate the chemical conversion process of fuel into combustion energy (\dot{Q}_c). These combustion models accommodate Air Fuel Ratio (AFR) conditions in excess fuel, stoichiometry, and excess air states. The ThePOCI application allows users to calculate these three combustion scenarios by inputting the equivalent ratio (λ) value based on the following equation.

$$\lambda = \frac{AFR_{actual}}{AFR_{Stoichiometry}} \quad (2)$$

The air fuel ratio (AFR) was calculated physically by comparing the mass of air (m_{air}) to the mass of fuel (m_{fuel}) using the following equation.

$$AFR = \frac{m_{air}}{m_{fuel}} = \frac{(V_{air} \times \rho_{air} \times A_{inlet,air}) \times 3600}{m_{fuel}} = \frac{(\lambda) \left(u + \frac{w}{4} - \frac{x}{2} + z \right) \times (MR_{air})}{m_{fuel}} \quad (3)$$

where V_{air} was the combustion air velocity (m/s), ρ_{air} represented as air density (kg/m³), dan $A_{inlet,air}$ was the air inlet area (m²). Additionally, the air mass can be calculated using combustion models by Boateng (2016) and Mawardi *et al.* (2024), where u is the number of carbon atoms (mol), w is the number of hydrogen atoms (mol), x is the number of oxygen atoms (mol), and z is the number of nitrogen atoms (mol). These atomic numbers are multiplied by MR_{air} as the relative molecular mass of air (kg/mol). The heat energy released during the combustion reaction was obtained from the difference in enthalpy. The enthalpy calculation to produce combustion energy in the ThePOCI application used the equation in the study of Mawardi *et al.* (2024). Once the combustion energy is known, the combustion efficiency (η_c) is calculated as the percentage ratio of combustion energy (\dot{Q}_c) to combustion input energy (\dot{Q}_{in}) using the following relation.

$$\eta_c = \frac{\dot{Q}_c}{\dot{Q}_{in}} \times 100\% \quad (4)$$

Combustion energy can be released into the environment through the furnace wall by conduction (\dot{Q}_{cond}), convection (\dot{Q}_{conv}), and radiation (\dot{Q}_{rad}). Under steady-state conditions, heat transfer through the furnace wall is constant because there is no heat accumulation as the system reaches thermal equilibrium (Mo *et al.*, 2019) so the conductive heat loss (\dot{Q}_{cond}) can be neglected. The convective heat loss \dot{Q}_{conv} was calculated according to the following equation (Holman, 2010):

$$\dot{Q}_{conv} = hA_w(T_w - T_{ai}) \quad (5)$$

where A_w represented as the wall surface area (m²), T_w represented as the wall temperature (K), dan T_{ai} represented as the inlet air temperature (K), and h represented convective heat transfer coefficient (kW/mK) which was calculated using the following equation.

$$h = \frac{Nu \times k}{L} \quad (6)$$

where Nu is the Nusselt number, k is the thermal conductivity of air and flue gas (kW/m K), and L is the wall length (m). Using a blower causes forced convection, and the Nusselt number (Nu) is based on the Reynolds number (Re).

$$\text{Re} = \frac{VL}{\nu} \quad (7)$$

where V is the velocity of air or flue gas (m/s) and ν is the kinematic viscosity of air and flue gas (m²/s). The Nusselt number calculation based on turbulent and laminar flow, as seen from the Reynolds number, is expressed as follows.

$$\text{Nu}_{\text{turbulent}} = 0.37 \text{Re}^{\frac{4}{5}} \text{Pr}^{\frac{1}{3}} \quad (8)$$

$$\text{Nu}_{\text{laminar}} = 0.664 \text{Re}^{\frac{1}{2}} \text{Pr}^{\frac{1}{3}} \quad (9)$$

Pr represents Prandtl number obtained from the REFPROP version 10 software with a call function embedded in the application using Python. In addition, \dot{Q}_{rad} as heat loss through radiation (kW) was represented in the following equation (Holman, 2010).

$$\dot{Q}_{\text{rad}} = \varepsilon \sigma A_w (T_w - T_{\text{ai}}) \quad (10)$$

where ε was represented as material emissivity and σ is the Stefan-Boltzmann constant (kW/m²K⁴). Heat loss also occurs due to combustion air heating and furnace ventilation (\dot{Q}_{vent}). The POCI application inputs the estimated heat loss in the form of air heat loss percentage (ALP) and was calculated using the following equation.

$$\dot{Q}_{\text{vent}} = \frac{\text{ALP} \times (\dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}})}{100} \quad (11)$$

The amount of heat energy loss (\dot{Q}_{loss}) and the useful heat energy (\dot{Q}_{g}) were calculated according to the following equations.

$$\dot{Q}_{\text{loss}} = \dot{Q}_{\text{conv}} + \dot{Q}_{\text{rad}} + \dot{Q}_{\text{vent}} \quad (12)$$

$$\dot{Q}_{\text{g}} = \dot{Q}_{\text{c}} - \dot{Q}_{\text{loss}} \quad (13)$$

The furnace efficiency (η_f) and thermal efficiency (η_{th}) of combustion were calculated using the equations.

$$\eta_f = \frac{\dot{Q}_{\text{g}}}{\dot{Q}_{\text{c}}} \times 100\% \quad (14)$$

$$\eta_{\text{th}} = \frac{\dot{Q}_{\text{g}}}{\dot{Q}_{\text{in}}} \times 100\% \quad (15)$$

The next stage involved calculations for the steam power generation system, including the pump, boiler, turbine, and condenser components. Calculations for the pump to determine its power were performed using the following equation (Moran *et al.*, 2014).

$$\dot{W}_{\text{pump}} = \dot{m}_{\text{ref}} \times (h_2 - h_1) \quad (16)$$

where \dot{W}_{pump} was the pump power (kW), \dot{m}_{ref} was the mass flow rate of the working fluid (kg/s), h_2 was the enthalpy of the working fluid leaving the pump (kJ/kg), and h_1 was the enthalpy of working fluid entering the pump (kJ/kg). The compressed working fluid flowed toward the boiler system. Numerical optimization based on the successive substitution method was used to calculate the temperature of the working fluid exiting the boiler based on the relationship between the heat transfer rate and the logarithmic mean temperature difference (LMTD) applied to the boiler system to calculate the working fluid temperature exiting the boiler.

$$q = U \times A_{\text{outtube}} \times \text{LMTD} \quad (17)$$

$$\text{LMTD} = \frac{(T_{\text{infg}} - T_{\text{outref}}) - (T_{\text{outfg}} - T_{\text{inref}})}{\ln \left[\frac{(T_{\text{infg}} - T_{\text{outref}})}{(T_{\text{outfg}} - T_{\text{inref}})} \right]} \quad (18)$$

where q was the heat transfer rate (W), U was the overall heat transfer coefficient (W/m^2), T_{inref} as the temperature of the working fluid entering the boiler (K), T_{outref} was the outlet fluid temperature of the boiler (K), T_{infg} was the inlet flue gas temperature of the boiler (K), and T_{outfg} was the outlet flue gas temperature of the boiler (K). Amount of heat energy entering the system through the boiler was calculated using the boiler outlet working fluid temperature obtained and the following equation (Moran *et al.*, 2014).

$$\dot{Q}_{boiler} = \dot{m}_{ref} \times (h_3 - h_2) \quad (19)$$

where \dot{Q}_{boiler} was the energy input to the boiler (kW), h_3 was the enthalpy of the working fluid leaving the boiler (kJ/kg), and h_2 was the enthalpy of the working fluid entering the boiler (kJ/kg). Pressurized steam flows to the turbine, generating a certain amount of power based on the following equation (Moran *et al.*, 2014).

$$\dot{W}_{turbine} = \dot{m}_{ref} \times (h_3 - h_4) \quad (20)$$

where $\dot{W}_{turbine}$ was the turbine power (kW), h_3 was the enthalpy of the working fluid entering the turbine (kJ/kg), and h_4 was the enthalpy of the working fluid leaving the turbine (kJ/kg). The heat rejected at the condenser component after passing through the turbine is calculated using the following equation (Moran *et al.*, 2014).

$$\dot{Q}_{condenser} = \dot{m}_{ref} \times (h_4 - h_1) \quad (21)$$

where $\dot{Q}_{condenser}$ was the energy output of (kW), and h_4 was the enthalpy of the working fluid entering the condenser (kJ/kg), and h_1 was the enthalpy of the working fluid leaving the condenser (kJ/kg). The performance of a steam power plant was represented by several parameters calculated using the following equation (Cengel & Boles, 2015; Moran *et al.*, 2014).

$$\dot{W}_{net} = \dot{W}_{turbine} - \dot{W}_{pump} \quad (22)$$

$$BWR = \frac{\dot{W}_{pump}}{\dot{W}_{turbine}} \quad (23)$$

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{boiler}} \times 100\% \quad (24)$$

$$\eta_{carnot} = \left(1 - \frac{T_{condenser}}{T_{boiler}} \right) \times 100\% \quad (25)$$

where \dot{W}_{net} was the net power (kW), BWR was the Back Work Ratio, η_{th} was the thermal efficiency of steam power plants (%), $T_{condenser}$ was condenser outlet temperature (K), and T_{boiler} as boiler outlet temperature (K). The next stage was to calculate the system's emission load using the life cycle climate performance (LCCP) equation following the calculations in the study by Azhari *et al.* (2025).

2.5. Design System

The system design consists of three stages: database design, back-end functions, and front-end functions. The application usage flow was studied by creating flowcharts to determine the exact working mechanism of the application. The application usage flow was presented in Figure 4. It is a reference for developing the user interface to make the data input and output mechanisms easier to understand. Understanding the data input and output mechanisms is a framework for building the ThePOCI application database system. Based on data input and output logic, the composition of entities and attributes is defined to form the ThePOCI database tables. The relationships between calculation variables are used as a reference to identify primary keys and foreign keys, thereby forming relationships within the database structure. The database structure design follows the Entity Relationship Diagram in Figure 5. Subsequently, development is carried out by designing the data transaction flow involving user interactions, the application interface, the database, and the application's back-end functions. As the primary actors, users are designed to input data parameters for calculations through the user interface developed using PHP programming. Next, the user instructs the PHP page to save the input data to MySQL through the button system available on the PHP page. The

user also gives the command to calculate the input data through the button system on the PHP page to activate the Python programming function. The Python programming function retrieves input data from the database, calculates the input data, and returns the calculation results to the database. In the final stage, the database sends the calculation results to the output page to be displayed on the interface. The design of the data transaction flow between the user, application interface, application back-end function, and database is shown in the sequence diagram in Figure 6. The implementation was carried out by developing the ThePOCI application, which involved several software tools described in subsection 2.1 Tools and Materials.

2.6. System Testing

The functional testing phase uses the black box method, which focuses on testing the functionality of the software from the user's perspective (Rahadi & Vikasari, 2020). Features are declared to have passed the test if they function as intended, while features that fail the test are noted for application improvement.

2.7. Validation

Validation was carried out by comparing the accuracy of the ThePOCI application's calculations with the test results. The Combustion Analysis module was validated using three parameters, namely Flue gas temperature (T_{fg}), Working fluid out boiler temperature (T_{outref}), and Turbin power ($W_{turbine}$). The Steam Power Plant Design module was validated with references from research (Safarian & Aramoun, 2015) for ideal conditions, with validated parameters being boiler input energy, condenser output energy, pump power, turbine power, net power, and thermal efficiency. Actual conditions were validated using research (Akkaya, 2017).

Validation was performed using the Mean Absolute Percentage Error (MAPE) method following the equation below (Sheikh & Unde, 2012).

$$MAPE = \frac{\sum_{i=1}^n (x_i - f_i)}{x_i} \quad (26)$$

where x_i was ThePOCI calculation data result, f_i was the experimental data, and n was the amount of data. The performance of ThePOCI application was evaluated from MAPE values. According to Maruddani & Trimono, (2018), the accuracy of prediction values are categorized as highly accurate with $MAPE < 10\%$, accurate ($11\% < MAPE < 20\%$), reasonable prediction ($21\% < MAPE < 50\%$), and inaccurate prediction ($MAPE > 51\%$).

3. RESULTS AND DISCUSSION

3.1. System Design and Implementation

The system design focuses on database design, operational procedures, and user interface. Database design refers to the entity relationship diagram in Figure 3. Application operational procedures are designed based on the application usage flow (Figure 4) and data calculation transaction mechanisms based on sequence diagrams (Figure 6). ThePOCI application operational procedures were developed with one actor, namely the user. The user's main activities are shown in the use case diagram in Figure 7. User activities are generally broken down in the user activity diagram in Figure 8 to illustrate the interaction between the user, the ThePOCI application, and the developed database.

The next stage involves implementing the system design by designing a virtual database system using MySQL software, designing the system operational flow using Python programming, and designing the application interface using PHP programming. The system interface design is implemented through scripting to obtain the main application interface shown in Figure 9.

The research focuses on developing the Steam Power Plant Design and Combustion Analysis modules. The Steam Power Plant Design module is used to analyze steam power plant systems and is not connected to the combustion system. In contrast, the combustion analysis module is provided to analyze steam power plant systems integrated with the combustion system.

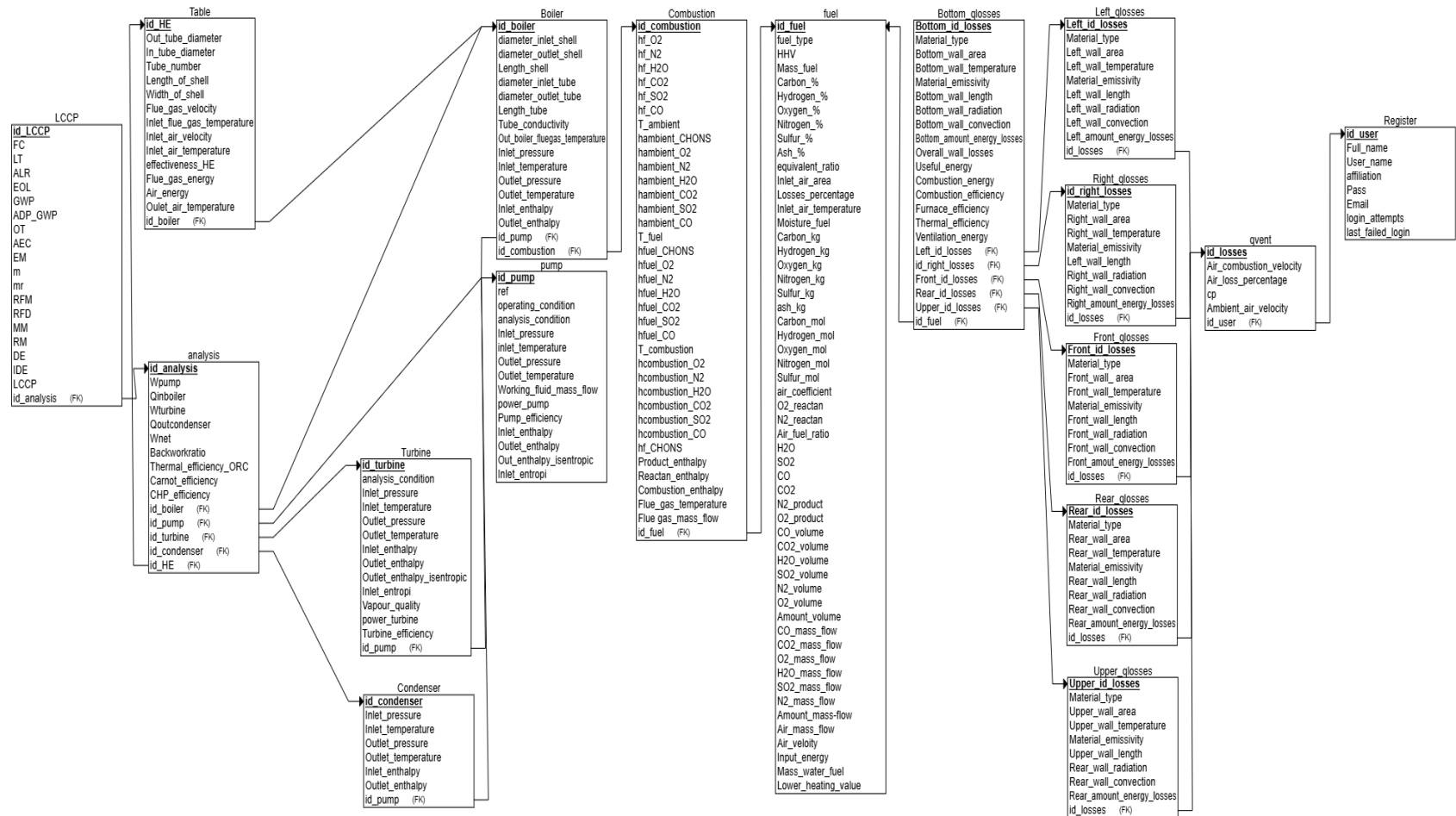


Figure 5. Entity relationship diagram database ThePOCI application

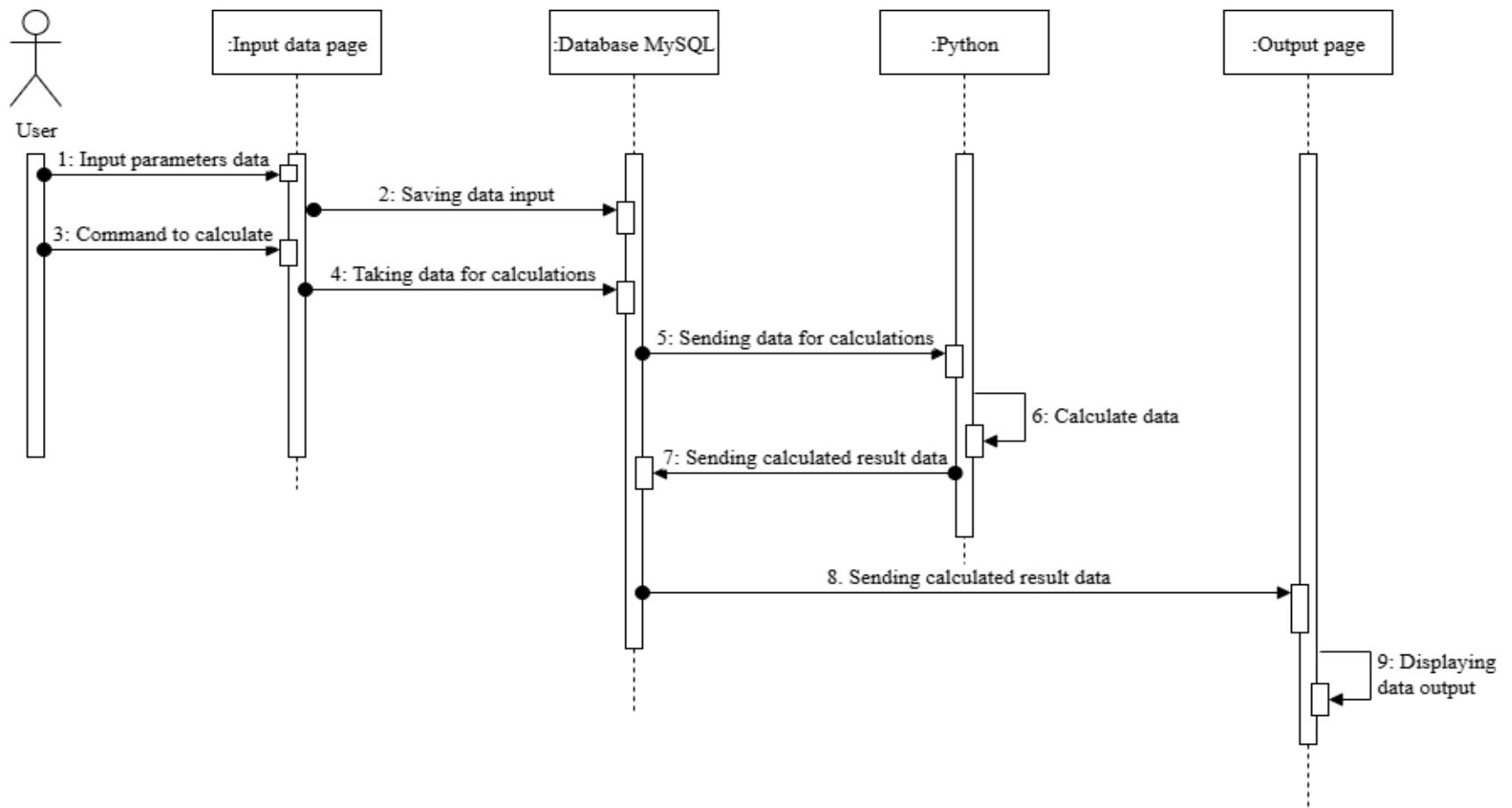


Figure 6. Sequence diagram data flow in ThePOCI application

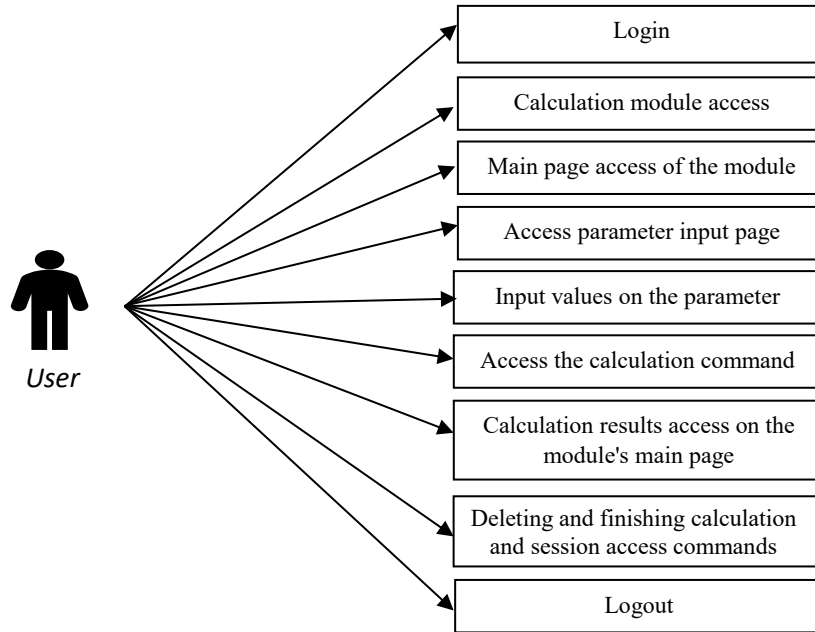


Figure 7. Use case diagram user application ThePOCI Deleting and finishing calculation and session access commands

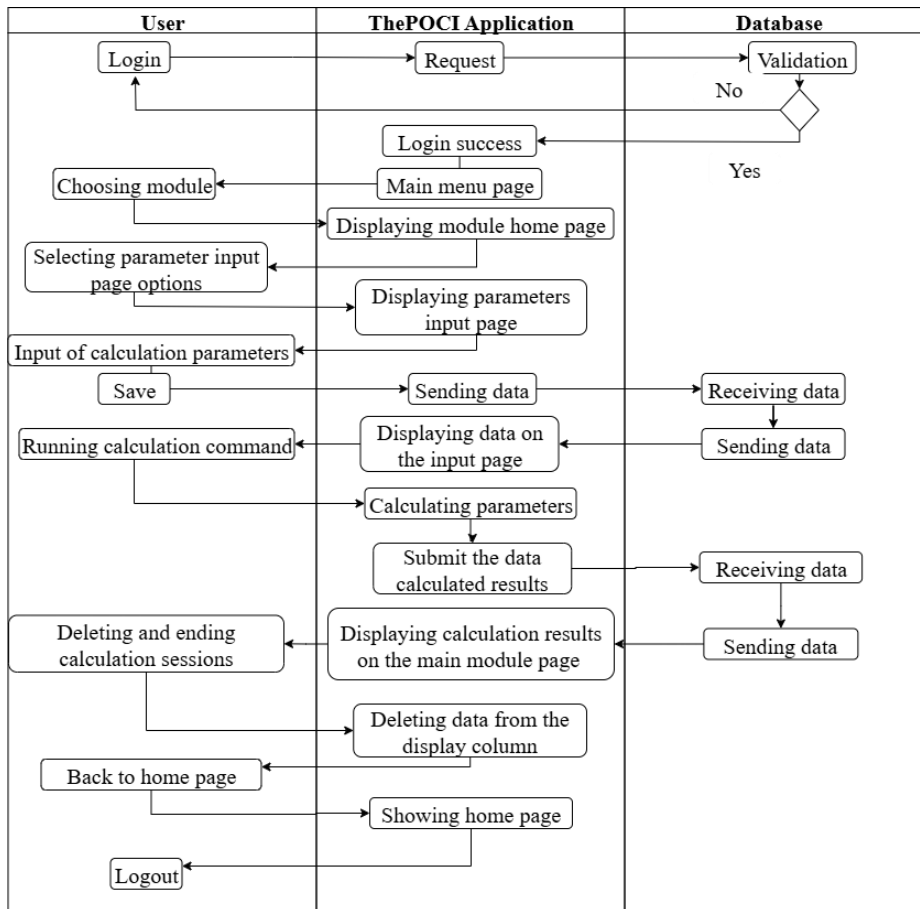


Figure 8. Activity diagram ThePOCI application

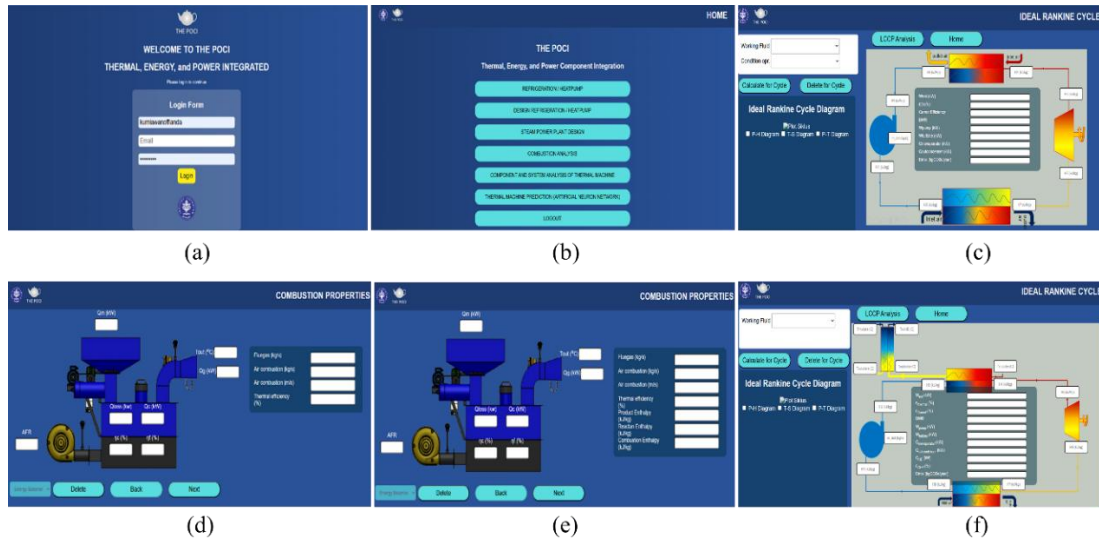


Figure 9. The main view of the ThePOCI application: (a) login, (b) main menu, (c) Steam Power Plant Design module, (d) thermal-based Combustion Analysis module, (e) material-based Combustion Analysis module, (f) combustion system integrated system analysis results

The combustion analysis module is the second module developed in this study. The combustion analysis module accommodates combustion system calculations using three thermal-based models, material-based models with estimated percentage loss inputs, and material-based models with furnace wall loss inputs. The thermal-based model accommodates users who do not have proximate and ultimate fuel characteristic data. In the thermal-based method, users only need to input combustion efficiency to estimate the energy produced from the combustion process. The material-based combustion method with energy loss percentage input does not include heat loss analysis through the furnace walls. However, users only need to input estimated energy loss as a percentage of the furnace to be designed. The material-based combustion method with energy loss percentage input was developed to accommodate users who will perform the initial design of the combustion furnace system and, therefore, do not yet have furnace wall temperature data. The material-based method with input of furnace wall losses accommodates users who require analysis of the combustion furnace system after completion. Combustion and enthalpy models are implemented in the material-based combustion analysis. The calculation results from the combustion analysis module are displayed on the pages in Figures 7d and 7e. The next button is used for users to continue the analysis to the page shown in Figure 2f.

3.2. ThePOCI Application Functional Testing

Functional testing of ThePOCI application using the black box method with test results shown in Table 1.

Table 1. Functional test results of the application using the black box method

No	Function	Testing procedure	Result
1	Login	Ensure users can log in to the system through https://thepoci.id/	Succeed
2	Access security	Ensure users cannot log in to other pages	Succeed
3	Access to the main menu	Confirm on the main page	Succeed
4	Access the field	Ensure each input field is accessible, populated and deleted	Succeed
5	Access to choose the choice of furnace wall material	Ensure material selection is available with thermal conductivity columns that can be filled in and displayed on the interface	Succeed
6	Access selects fuel type	Ensure the choice of fuel type and nature is filled	Succeed
8	Access to the selection of working fluids	Ensure the selection of working fluids is available and displayed	Succeed
9	Display parameters of the calculation results	Ensure the system displays every calculation parameter	Succeed
10	Displays the results of the working fluid selection in the input column	Ensure that the results of the selected working fluids can be displayed on every input page	Succeed

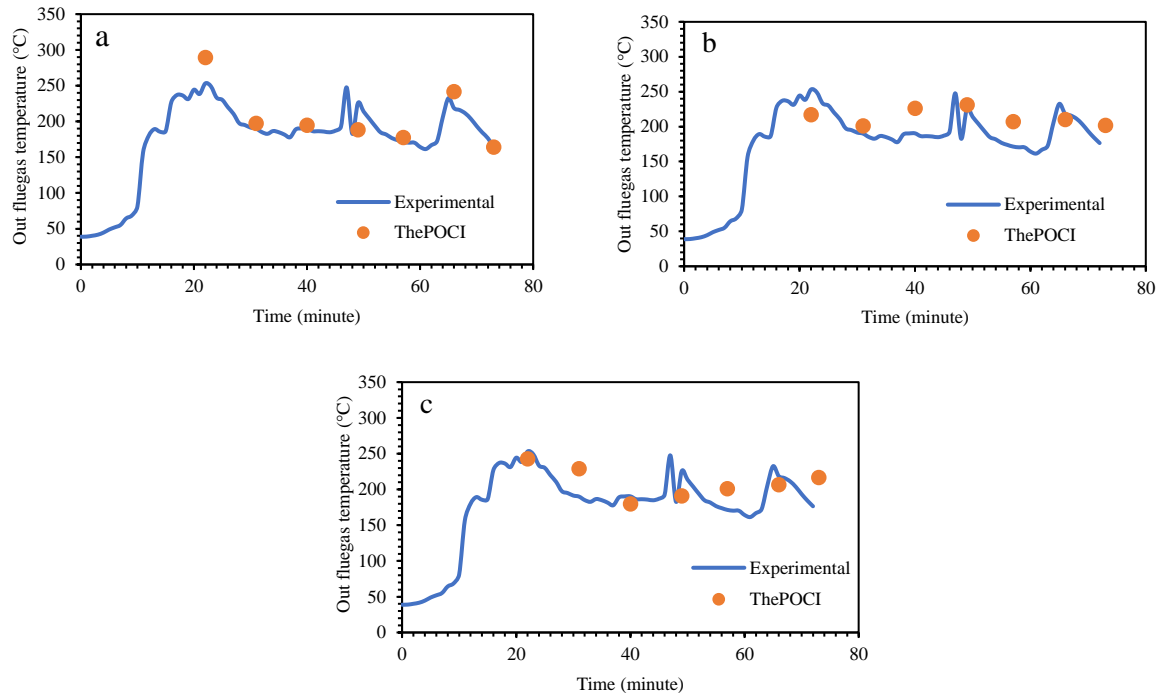


Figure 10. Flue gas temperature validation: (a) Thermal-based model, (b) Material-based model of the input percentage of losses, (c) Material-based model of furnace wall temperature input

3.3. Validation of Combustion Analysis Module

3.3.1. Flue gas Combustion Output Temperature Validation

The validation of flue gas temperature is shown in Figure 10. Model two has the highest error (13.08%), while model one has the lowest (1.67%). The variables composing the numerical model have uncertainty ranges originating from the measurement process and measuring instruments. Variable uncertainty can propagate, leading to larger uncertainty ranges in calculation results due to the accumulation of uncertainty from the model's constituent variables (Sharifian *et al.*, 2019; Faes & Moens, 2020). Model one, a thermal-based model, comprises input data from physical system experiments. In contrast, models two and three include additional input data on the proximate and ultimate characteristics of the fuel from laboratory tests rather than physical system experiments. The combustion enthalpy is obtained from thermodynamic table interpolation (Cengel & Boles, 2015). The increase in proximate, ultimate, and combustion enthalpy input data that did not originate from physical system testing increased the uncertainty range of models two and three. Additionally, models two and three were based on mass balance calculations that referred to the combustion model. The calculation results of combustion characteristic variables based on the combustion chemical reaction model approach are highly dependent on the initial determination of the fuel's ultimate and proximate mass fractions. The initial determination of the ultimate and proximate fractions of the fuel determines the composition of combustion products, which impacts the increase in the uncertainty range of combustion characteristic calculations (Paraschiv *et al.*, 2020; Popescu *et al.*, 2020). Fuel decomposition during combustion is influenced by combustion temperature, so the proportion of compounds formed can vary based on temperature (Popescu *et al.*, 2020; Thabit *et al.*, 2022). Combustion temperature during the experimental process tends to fluctuate. In contrast, the calculation of flue gas temperature from models two and three is based on the assumption that the composition of combustion products follows the combustion chemistry model. Therefore, the uncertainty range increases in the calculation results of flue gas variables in models two and three due to the accumulation of uncertainty from the combustion chemistry model. Model three has a lower uncertainty range than model two because the additional wall temperature input data in model three is derived from experimental data of the physical system, making model three's calculation results closer to experimental data. However, models one and three have limitations because they require thermal

characteristic input data obtained from experiments, so they can only be used after conducting experiments on the entire physical system. Users requiring an initial system design without prior physical system experiments can use model two. Flue gas temperature validation of combustion results was conducted by *Yentumi et al. (2022)* with an error of 14.7%, while *Mawardi et al. (2024)* reported the highest error for flue gas temperature validation at 19.3%. In general, the error of each model is still within an acceptable range. This indicates that each model developed from the ThePOCI application can simulate combustion systems with an acceptable range of uncertainty, particularly Model 1, which is highly suitable for thermal characterization analysis of combustion systems based on physical system.

3.4.2. Boiler Output Working Fluid Temperature Validation

The results of validating the working fluid temperature output from the boiler can be seen in Figure 11. The boiler outlet fluid temperature shows a phenomenon similar to the flue gas temperature, which produces an error in model two (16.93%) and the lowest in model one (9.53%). The propagation of uncertainty from flue gas temperature data affects the boiler outlet working fluid temperature because flue gas temperature is one of the variables in the equation used to calculate the boiler outlet working fluid temperature. *Cai et al. (2020)* reported a validation result of 13.95% for the boiler outlet working fluid temperature in an ORC system. *Azhari et al. (2025)* reported a validation result of 7% for the boiler outlet working fluid temperature. The overall validation results indicate that the calculation model within the ThePOCI application can estimate the boiler outlet working fluid temperature within an acceptable uncertainty range (MAPE < 20%).

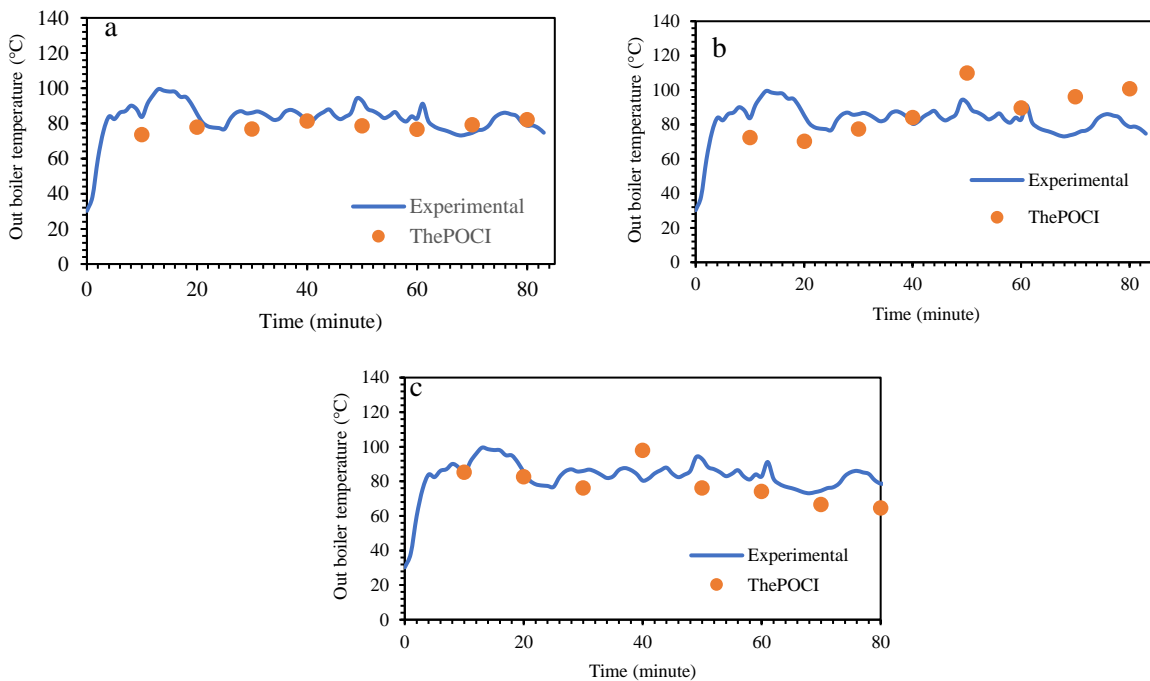


Figure 11. Boiler outlet working fluid temperature validation: a) Thermal-based model, (b) Loss-based model, (c) Wall temperature input-based model

3.4.3. Turbine Power Validation

The results of turbine power validation under steady state conditions are shown in Figure 12. Turbine power validation shows the highest value in model two (10.39%) and the lowest in model one (7.49%). The heating process inside the boiler influences turbine output power, so uncertainty propagation occurs in turbine power because it consists of boiler outlet temperature variables. However, pump speed, pressure, and evaporation temperature changes are directly proportional to turbine power (*Xu et al., 2017*), so inputting mass flow rate, pressure, and turbine temperature

variables that match the physical system experiment results can reduce errors. [Dickes *et al.*, \(2017\)](#) reported turbine power validation errors up to 17.95%, while a 5% error was obtained in the study ([Xu *et al.*, 2017](#)). Based on the MAPE result, the validation results of the model developed in the combustion analysis module can simulate the steam power generation system within an acceptable uncertainty range (<20%).

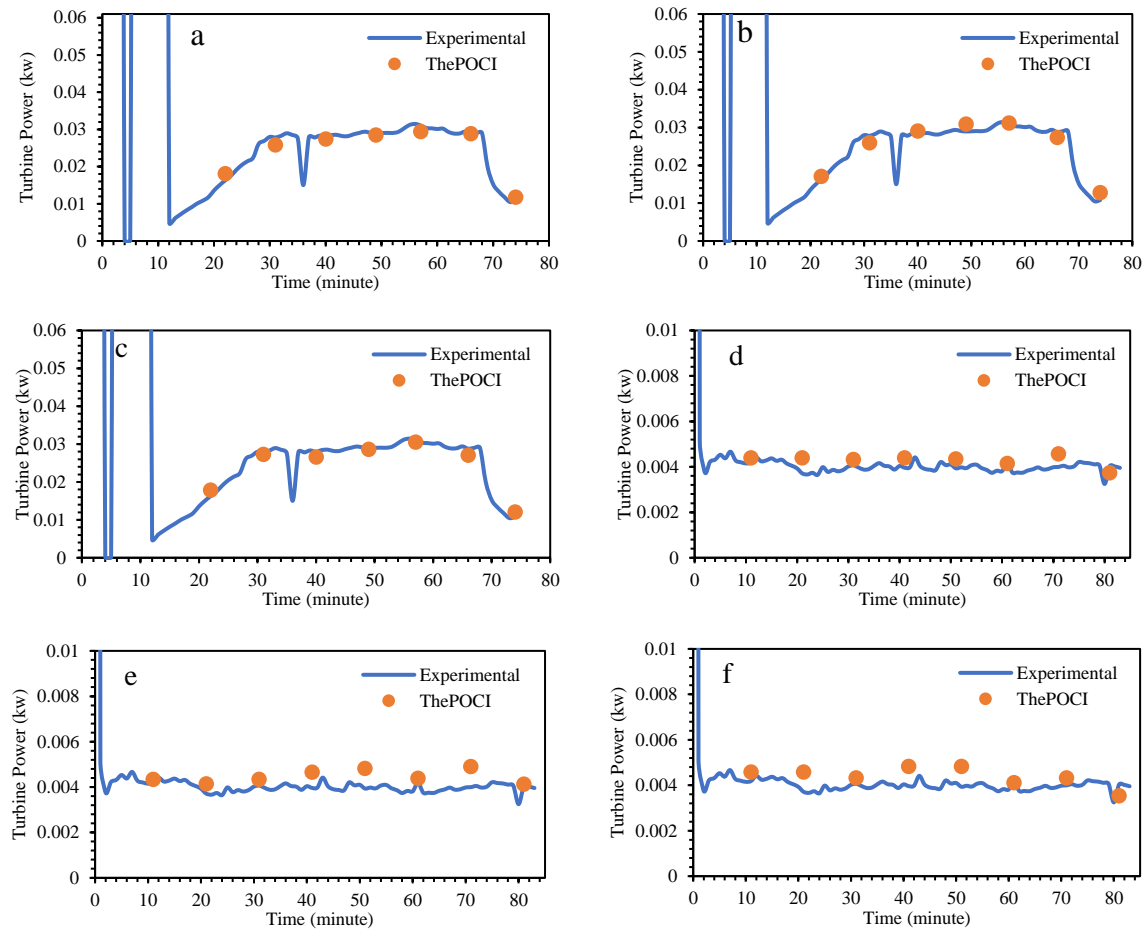


Figure 12. Turbine power validation: (a) Model 1 fuel calliandra, (b) Model 2 fuel calliandra, (c) Model 3 fuel calliandra, (d) Model 1 fuel sengon, (e) Model 2 fuel sengon, (f) Model 3 fuel sengon.

3.5. Steam Power Plant Design Module Validation

The Steam Power Plant Design module is one of the modules that has been developed in ThePOCI application. The validation of the Steam Power Plant Design module was conducted by comparing the application's calculation results with research studies ([Safarian & Aramoun, 2015](#)) for ideal conditions and ([Akkaya, 2017](#)) for actual conditions, as shown in Tables 2 and 3. The validation results for the steam power plant design module indicate that the MAPE value falls within the highly accurate category (< 10%). The error range results confirm that the ThePOCI application is capable of accurately representing a steam power plant system, making it a viable methodological option for physical system prototyping without incurring additional costs. The research by [Giardiello *et al.* \(2022\)](#) validated the organic Rankine cycle system with an average error of 6.2%. The organic Rankine cycle system was previously validated with an average error of 4.8% ([Davidy, 2021](#)).

The development of the ThePOCI application is currently limited to simulating steam power plant systems based on the ideal Rankine cycle with assumptions under steady-state conditions. Developing the ThePOCI application to accommodate transient conditions presents an opportunity for further research. Additionally, development for more

complex Rankine cycle analysis, such as the addition of preheating devices, modification of system component geometry, and modification of more dynamic system component specifications, presents further research opportunities.

Table 2. Validation results of the Steam Power Plant Design module under ideal operating conditions

Parameters	(Safarian & Aramoun, 2015)	This Research (ThePOCI)	APE (%)
Q_{in} (kW)	252	256.30	1.71
Q_{out} (kW)	202	205.51	1.74
$W_{turbine}$ (kW)	51	52.77	3.47
W_{pump} (kW)	1.96	1.98	1.02
W_{net} (kW)	49.04	50.79	3.56
η_{th} (%)	19.46	19.82	1.85
MAPE (%)			2.22

Table 3. Validation of the Steam Power Plant Design module under actual operating conditions

Parameters	(Akkaya, 2017)	This Research (ThePOCI)	APE (%)
Q_{out} (kW)	2,514	2,499.03	0.60
W_{pump} (kW)	1.96	1.98	1.02
W_{net} (kW)	303.50	299.12	1.44
η_{th} (%)	10.80	10.75	0.45
MAPE (%)			0.88

Table 4. Steam power generation system emission load

Fuel	Emissions (kgCO ₂ e/kW)	Net Power (kW)
Calliandra	3741.20	0.026
Sengon	4895.26	0.019

3.6. System Emission Load Analysis

LCCP analysis is used to determine the emission load of steam power generation systems by accommodating refrigerant usage factors, especially in organic Rankine cycle (ORC) systems. Biomass power plant emission factors are included in LCCP calculations with the assumption that carbon is also produced from transportation, combustion, and potential disruption of the natural carbon cycle (Ahamer, 2022). Model one was selected for LCCP calculations due to its better MAPE value. The results of the emission load calculations are shown in Table 4. Fuel emissions from sengon are higher than those from calliandra. In the LCCP equation, the system's net power output serves as the divisor, so an increase in net power output tends to reduce the system's emission load. Table 4 shows that the net power calculated using ThePOCI application yields an average power output of 0.026 kW for calliandra and 0.019 kW for sengon fuel. The study by Kusananto *et al.* (2024) reported that an increase in the calorific value of fuel tends to increase the power output generated by the power generation system. The results of independent laboratory tests showed that the calorific value of calliandra was 20,007.89 kJ/kg, while that of sengon was 19,911.7 kJ/kg. The calorific value represents the thermal energy potential that can be converted into power, so an increase in the calorific value has the potential to increase the power output of the steam power generation system. Such results indicate that selecting fuel with a high calorific value can help reduce system emissions. The study by Lan *et al.* (2022) reported the same phenomenon, that an increase in energy and temperature of the heat source impacts a reduction in power generation system emissions. Thus, calliandra may be more favorable in ORC-based systems for minimizing environmental impacts due to its higher thermal performance and lower carbon output per kW generated. Additionally, LCCP-based emission calculations also consider the amount of refrigerant used in the system, so an increase in the capacity of an ORC-based steam power generation system leads to an increase in refrigerant usage, which ultimately results in higher emissions. He *et al.* (2024) reported R134a emissions of 3,777 kgCO₂e/kW, while Tovar *et al.* (2024) recorded emissions of 109,933.63 kgCO₂e for a turbine power of 188.88 kW in a biomass system.

4. CONCLUSION

ThePOCI thermal system application has been developed with two main modules, Steam Power Plant Design and Combustion Analysis, each serving its respective function. The Combustion Analysis module exhibited the largest calculation deviation in the material-based model with energy loss percentage input. Based on the variables of flue gas temperature, boiler exit working fluid temperature, and turbine power —13.08%, 16.93%, and 10.39%, respectively— the results remain within the accurate range. Validation of the Steam Power Plant Design module yielded calculation deviations for ideal and actual operating conditions of 2.22% and 0.88%, respectively, which fall into the highly accurate category. In general results, the validation results confirm that ThePOCI application is capable of accurately simulating the physical system of a steam power plant based on the ideal Organic Rankine Cycle (ORC). The systems emission calculations indicate potential for further research on using calliandra biomass in an ORC-based steam power plant, identified as the fuel producing the lowest emissions at 3,742.20 kgCO₂e/kW compared to Sengon of 4,895.26 kgCO₂e/kW. ThePOCI application is expected to contribute to the education sector, particularly as a teaching tool for thermodynamics and Rankine cycle-based energy conversion analysis. In the industrial sector, it is expected to assist in steam power plant prototyping processes based on system modeling and simulation. Furthermore, integrate a biomass furnace system, an ORC-based steam power plant system, and an emission calculation module can support the development of low-emission energy conversion systems, thereby contributing to greenhouse gas mitigation and the advancement of sustainable technologies.

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REFERENCES

- Ahamer, G. (2022). Why biomass fuels are principally not carbon neutral. *Energies*, *15*(24), 9619. <https://doi.org/10.3390/en15249619>
- Akkaya, A.V. (2017). Performance analyzing of an organic Rankine cycle under different ambient conditions. *Journal of Thermal Engineering*, *3*(5), 1498–1504. <https://doi.org/10.18186/journal-of-thermal-engineering.338897>
- Al Azhari, L.M.F.A., Yulianto, M., & Hartulistiyoso, E. (2025). ORC performance study with R32 and R134a using biomass as an energy source. *Jurnal Teknik Pertanian Lampung*, *14*(1), 118–129.
- Boateng, A.A. (2016). Combustion and flame. *Rotary kilns (2nd ed.): Transport phenomena and transport processes*, 107–143. <https://doi.org/10.1016/B978-0-12-803780-5.00006-X>
- Cai, J., Shu, G., Tian, H., Wang, X., Wang, R., & Shi, X. (2020). Validation and analysis of organic Rankine cycle dynamic model using zeotropic mixture. *Energy*, *197*, 117003. <https://doi.org/10.1016/j.energy.2020.117003>
- Cengel, Y. A., & Boles, M. A. (2015). *Thermodynamics an Engineering Approach* (8th ed.). Mc Graw-Hill Education.
- Chen, D., Han, Z., Bai, Y., Guo, D., Zhao, L., & Li, P. (2022). Layout comparison and parameter optimization of supercritical carbon dioxide coal-fired power generation systems under environmental and economic objectives. *Entropy*, *24*(8), 1123. <https://doi.org/10.3390/e24081123>
- Davidy, A. (2021). Thermodynamic design of organic Rankine cycle (ORC) based on petroleum coke combustion. *ChemEngineering*, *5*(3), 37. <https://doi.org/10.3390/chemengineering5030037>
- Dickes, R., Dumont, O., Daccord, R., Quoilin, S., & Lemort, V. (2017). Modelling of organic Rankine cycle power systems in off-design conditions: An experimentally-validated comparative study. *Energy*, *123*, 710–727. <https://doi.org/10.1016/j.energy.2017.01.130>
- Faes, M., & Moens, D. (2020). Recent trends in the modeling and quantification of non-probabilistic uncertainty. *Archives of Computational Methods in Engineering*, *27*, 633–671. <https://doi.org/10.1007/s11831-019-09327-x>

- Giardiello, G., de Nola, F., Ghezzi, G., Gimelli, A., Iossa, R., Langella, G., & Sessa, B. (2022). Model and transient control strategy design of an organic Rankine cycle plant for waste heat recovery of an internal combustion engine. *Journal of Physics: Conference Series*, **2385**(1), 012118. <https://doi.org/10.1088/1742-6596/2385/1/012118>
- Hartulistiyoso, E., Suchahyo, L., Yulianto, M., & Sipahutar, M. (2020). Thermal efficiency analysis of Organic Rankine Cycle (ORC) system from low-grade heat resources using various working fluids based on simulation. *IOP Conference Series: Earth and Environmental Science*, **542**(1), 012047. <https://doi.org/10.1088/1755-1315/542/1/012047>
- He, Y., Zheng, Y., Zhao, J., Chen, Q., & Zhang, L. (2024). Study of a novel hybrid refrigeration system, with natural refrigerants and ultra-low carbon emissions, for air conditioning. *Energies*, **17**(4), 880. <https://doi.org/10.3390/en17040880>
- Holman, J.P. (2010). *Heat Transfer* (10th ed.). Mc Graw-Hill.
- Hong, C.-S., & Lee, E.-B. (2018). Power plant economic analysis: Maximizing lifecycle profitability by simulating preliminary design solutions of steam-cycle conditions. *Energies*, **11**(9), 2245. <https://doi.org/10.3390/en11092245>
- International Institute of Refrigeration. (2015). *Guideline for life cycle climate performance*. Life Cycle Climate Performance Working Group. <https://ref.org.ua/upload/iblock/bc0/IIR-Guideline-for-Life-Cycle-Climate-Performance-2015-English.pdf>
- Khankari, G., & Karmakar, S. (2017). 4-E Analysis of a Kalina cycle system 11 Integrated 500MWe Combined Thermal Power Plant. *IEEE Region 10 Annual International Conference, Proceedings/TENCON, 2017-Decem*, 93–98.
- Kumar, A., & Ram, B. (2023). Application and significance of web-based library services. *International Research Journal of Modernization in Engineering Technology and Science*, **5**(5), 3397–3400. <http://dx.doi.org/10.56726/IRJMETS38970>
- Kusnanto, K., Harto, A.W., Wallitu, H., Facius, M.J., Afifah, N.A., & Tenggara, A.P. (2024). Analysis of the influence of variation in medical waste heating value on the electrical energy output of generator in medical waste cogeneration incinerator system using GateCycle solver. *Journal of Physics: Conference Series*, **2828**(1), 012050. <https://doi.org/10.1088/1742-6596/2828/1/012050>
- Lai, C.S., & Locatelli, G. (2021a). Valuing the option to prototype: A case study with generation integrated energy storage. *Energy*, **217**, 119290. <https://doi.org/10.1016/j.energy.2020.119290>
- Lai, C.S., & Locatelli, G. (2021b). Economic and financial appraisal of novel large-scale energy storage technologies. *Energy*, **214**, 118954. <https://doi.org/10.1016/j.energy.2020.118954>
- Lan, Y., Wang, S., Lu, J., Zhai, H., & Mu, L. (2022). Comparative analysis of organic Rankine cycle, Kalina cycle and thermoelectric generator to recover waste heat based on energy, exergy, economic and environmental analysis method. *Energy Conversion and Management*, **273**, 116401. <https://doi.org/10.1016/j.enconman.2022.116401>
- Maruddani, D.A.I., & Trimono, T. (2018). Modeling stock prices in a portfolio using multidimensional geometric Brownian motion. *Journal of Physics: Conference Series*, **1025**(1), 012122. <https://doi.org/10.1088/1742-6596/1025/1/012122>
- Mawardi, H., Hartulistiyoso, E., & Yulianto, M. (2024). Theoretical study of thermal characteristics of energy crop biomass combustion under various air conditions in an adiabatic furnace. *Jurnal Ilmiah Rekayasa Pertanian dan Biosistem*, **12**(2), 659. <https://doi.org/10.29303/jrpb.v12i2.659>
- Mayanti, B., Songok, J., & Helo, P. (2021). Multi-objective optimization to improve energy, economic and environmental life cycle assessment in waste-to-energy plant. *Waste Management*, **127**, 147–157. <https://doi.org/10.1016/j.wasman.2021.04.042>
- Mo, J.P.T., Cheung, S.C.P., & Das, R. (2019). Steady-state heat conduction systems. *Demystifying numerical models: Step-by-step modeling of engineering systems*, 61–85. <https://doi.org/10.1016/B978-0-08-100975-8.00004-7>
- M Moran, M.J., Shapiro, H.N., Boettner, D.D., & Bailey, M.B. (2018). *Fundamentals of engineering thermodynamics* (8th ed.). John Wiley & Sons Inc.
- O'Brien, J.A., & Marakas, G.M. (2010). *Management information systems* (10th ed.). McGraw-Hill Education.
- Ozorhon, B., Karatas, C.G., & Demirkesen, S. (2014). A web-based database system for managing construction project knowledge. *Procedia - Social and Behavioral Sciences*, **119**, 377–386. <https://doi.org/10.1016/j.sbspro.2014.03.043>
- Paraschiv, L.S., Serban, A., & Paraschiv, S. (2020). Calculation of combustion air required for burning solid fuels (coal/biomass/solid waste) and analysis of flue gas composition. *Energy Reports*, **6**(3), 36–45. <https://doi.org/10.1016/j.egyr.2019.10.016>
- Popescu, F., Mahu, R., Ion, I.V., & Rusu, E. (2020). A mathematical model of biomass combustion physical and chemical

- processes. *Energies*, **13**(23), 6232. <https://doi.org/10.3390/en13236232>
- Rahadi, N.W., & Vikasari, C. (2020). Pengujian software aplikasi perawatan barang milik negara menggunakan metode black box testing equivalence partitions. *Infotekmesin*, **11**(1), 57–61.
- Safarian, S., & Aramoun, F. (2015). Energy and exergy assessments of modified Organic Rankine Cycles (ORCs). *Energy Reports*, **1**, 1–7. <https://doi.org/10.1016/j.egy.2014.10.003>
- Sharifian, S., Sotudeh-Gharebagh, R., Zarghami, R., Tanguy, P., & Mostoufi, N. (2019). Uncertainty in chemical process systems engineering: A critical review. *Reviews in Chemical Engineering*, **37**(6), 687–714. <https://doi.org/10.1515/revce-2018-0067>
- Sheikh, S.K., & Unde, M.G. (2012). Short-term load forecasting using ANN technique. *International Journal of Engineering Sciences & Emerging Technologies*, **1**(2), 97–107. https://doi.org/10.7323/ijeset/v1_i2_12
- Thabit, Q., Nassour, A., & Nelles, M. (2022). Flue gas composition and treatment potential of a waste incineration plant. *Applied Sciences*, **12**(10), 5236. <https://doi.org/10.3390/app12105236>
- Tovar, J.M., Valencia Ochoa, G., & Molina, B. (2024). 3E comparative analysis of Brayton–ORC cycle using two thermal sources: Solar energy and coconut shell biomass. *Eng.* **5**(4), 3335–3357. <https://doi.org/10.3390/eng5040174>
- Xu, B., Rathod, D., Kulkarni, S., Yebi, A., Filipi, Z., Onori, S., & Hoffman, M. (2017). Transient dynamic modeling and validation of an organic Rankine cycle waste heat recovery system for heavy duty diesel engine applications. *Applied Energy*, **205**, 260–279. <https://doi.org/10.1016/j.apenergy.2017.07.038>
- Yassin, M.A.M., Shrestha, A., & Rabie, S. (2023). Digital twin in power system research and development: Principle, scope, and challenges. *Energy Reviews*, **2**(3), 100039. <https://doi.org/10.1016/j.enrev.2023.100039>
- Yentumi, R., Dorneanu, B., & Arellano-Garcia, H. (2022). Optimal operation of an industrial natural gas fired natural draft heater. *Chemical Engineering Journal Advances*, **11**, 100354. <https://doi.org/10.1016/j.ceja.2022.100354>
- Yildiz, E., Møller, C., & Bilberg, A. (2020). Virtual factory: Digital twin based integrated factory simulations. *Procedia CIRP*, **93**, 216–221. <https://doi.org/10.1016/j.procir.2020.04.043>