Design and Analysis of a Brayton Cycle Power Plant with Waste Heat Recovery for a 35-story Office Building in Lahore, Pakistan

Muhammad Azhaf Zeeshan[1], Amna Saleem[2], Muhammad Abdullah Zafar Ghauri[3]

Muhammad Muhaimin Zia[4], Abdullah Hamid[5], Muhammad Ammar Amer[6]

[1,2,3,4,5,6]SMME,NUST,Pakistan

[1]mzeeshan.ug22smme@student.nust.edu.pk; [2]asaleem.ug22smme@student.nust.edu.pk;
[3]mghauri.ug22smme@student.nust.edu.pk; [4]mzia.ug22smme@student.nust.edu.pk;
[5]ahamid.ug22smme@student.nust.edu.pk; [1]mamer.ug22smme@student.nust.edu.pk

***Abstract*— This paper explores the possibility of using a regenerative Brayton cycle with intercooling and reheating for power generation in a 35-story office building located in Lahore, Pakistan. The proposed system would incorporate the recovery of waste heat to take care of the building's heating needs. The cycles are studied for both ideal and non-ideal configurations, considering the efficiencies of different components and real-world constraints. The efficiency of using the waste heat for heating the building in Lahore's climate is also studied. The report goes on to detail possible ways in which the overall system efficiency could be optimized.**
Keywords*— Brayton Cycle, Intercooling, Reheating, Regenerative, Waste Heat Recovery, Building Energy Efficiency

I. INTRODUCTION

This report is a design and analysis of a power generation system applied to a 35-story office building in Lahore, Pakistan, seeking sustainability and energy management efficiency. It uses the Brayton cycle, which is a well-accepted thermodynamic cycle for power generation, with some major modifications to improve efficiency and meet the heating requirements of the building.

Two configurations of the Brayton cycle are considered in this report:

- Ideal Regenerative Brayton Cycle: This configuration incorporates intercooling and reheating stages for efficiency improvement in an ideal situation.
- Non-Ideal Regenerative Brayton Cycle: This configuration includes the actual component efficiencies and an effective 70% regenerator to be more realistic in a practical application.

The effectiveness of waste heat recovery, which is an important aspect of the design, has been evaluated to determine its potential to meet the heating needs of the building in Lahore's diverse climate.

Moreover, the report analyzes the design critically in light of key assumptions and justifications. It goes into missing elements that are important for real-world application and discusses possible strategies for optimizing the overall efficiency of the system.

As such, this report investigates these aspects to contribute to the development of feasible and sustainable power generation systems that harmonize well with building energy demands.

II. BUILDING LAYOUT

The target building has

- 35-story office complex
- Maximum capacity: 400 people per floor
- Cafes:
    - Full-size cafe on the 2nd floor
    - Half-size cafes on:
        - 13th floor
        - 26th floor
        - Rooftop floor

III. BUILDING HEATING DEMAND ESTIMATION

Site Survey:

1. 35-floor office building.
2. 50 rooms and can house up to 400 persons.
3. 4 fully functional cafes.
4. The café on the second floor occupies the complete floor while three cafes located on 13th and 26th floors occupy half of the space and the last one at the roof top.
5. Average daytime temperature in Lahore is 21C.
6. Desired indoor Temperature = 27 C.
7. Assumption: Rooftop café is open air and operational from 9 to 5 pm.

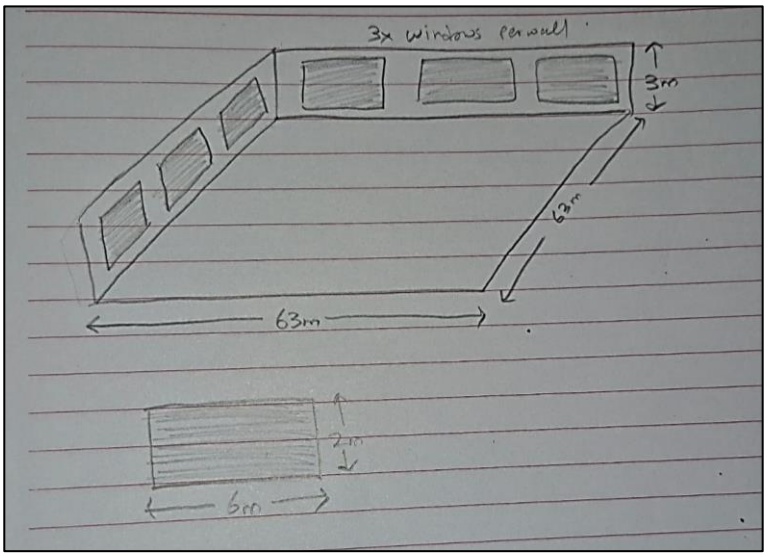


Figure 1: Assumed size of a floor and windows.

Building Dimensions Per Floor:

Floor= 63 x 63 = 3969 m^2

Height = 3m per floor

Window= 6 x 2 = 12m^2

Window area per floor= 12 x 12 = 144m2

Wall area per floor= (4x63x3)-144 =756 -144 = 612 m2

1. *Walls*

Surface Area: 612 m²

Material: Brick with plaster

Heat Transfer Coefficient (U): 1.5 W/m²K

Calculation:

$$Qwall = U * A * (To - Ti)$$

$$Qwall = 1.5\,W/m^2K * 612\,m^2 * (27°C - 21°C)$$

$$Qwall = 5508\,W$$

2. *Roof*

Surface Area: 3969 m²

Material: Concrete slab with insulation

Heat Transfer Coefficient (U): 0.7 W/m²K

Calculation:

$$Qroof = U * A * (To - Ti)$$

$$Qroof = 0.7\,W/m^2K * 3969\,m^2 * (27°C - 21°C)$$

$$Qroof = 16669.8\,W$$

3. *Windows*

Surface Area: 144 m²

Material: Double-glazed glass

Heat Transfer Coefficient (U): 2.8 W/m²K

Solar Transmission Coefficient (STC): 0.65

Solar Radiation: 500 W/m²

Calculation:

Conduction:

$$Qwindow_conduction = U * A * (To - Ti)$$

$$Qwindow_conduction = 2.8\,W/m^2K * 144\,m^2 * (27°C - 21°C)$$

$$Qwindow_conduction = 2419.2\,W$$

4. *Solar Gain:*

$$Qwindow_solar = STC * Solar\ Radiation * A$$

$$Qwindow_solar = 0.65 * 500\,W/m^2 * 144\,m^2$$

$$Qwindow_solar = 46800\,W$$

Total for Windows:

$$Qwindow_total = Qwindow_conduction + Qwindow_solar$$

$$Qwindow_total = 52444.8\,W$$

5. *Ventilation*

Air Change Rate: 0.7 changes per hour (volume = 11907 m³, so 8334.9 m³/h)

Calculation:

$$Qvent = \rho * Cp * V * (To - Ti)$$

$$Qvent = 1.225\,kg/m^3 * 1.005\,J/kg°C * 8334.9\,m^3/h * (27°C - 21°C)$$

$$Qvent = 61567.82\,W$$

6. *Internal Heat Sources*

Occupants: 400 x 150= 60000 W

Lighting: 3750 W

Electronic Equipment: 28750 W

Total for Internal Sources:

$$Qinternal = Qoccupants + Qlighting + Qelectronics + Qappliances$$

$$Qinternal = 92500\,W$$

$$Qtotal = (Qwall + Qwindow_total + Qvent - Qinternal)\,x\,36 + Qroof$$

$$= (5508 + 52444.8 + 61567.82 - 92500)\,x35 + 16669.8$$

$$= 962391.5\ W\ per\ hour$$

COP of HVAC System = 3

COP = Qtotal / Welect

$W_{electric}$ = 320797.17 W Requirement

IV . Proposed Cycle Configurations

This section explores two configurations of the Brayton cycle designed to generate electricity for the 35-story office building while addressing its heating needs through waste heat recovery.

A. Ideal Brayton Cycle with 2-stage intercooling and 2-stage reheating.

1) T-s Diagram

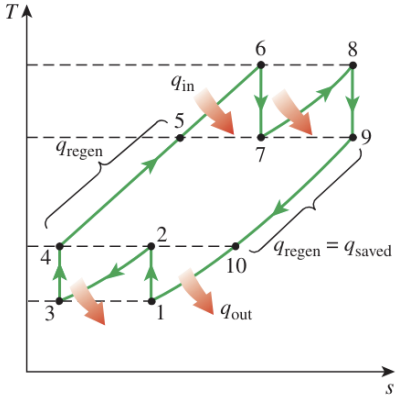


Figure 2:T-s Diagram of The Ideal Brayton Cycle

2) Schematic Diagram

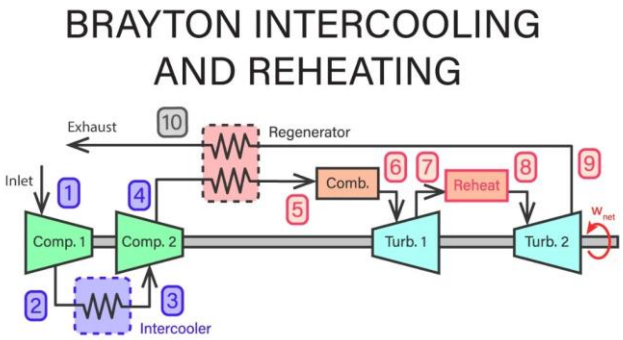


Figure 3:Schematic Diagram Of Brayton Cycle With Reheat And Intercooling

3) Work Input,Use and Requirement Calculation(Refer to Figure 1)

$Compressor\ Inlet = T_1 = 295K$
$Turbine\ Inlet = T_6 = 500K$
$Compression\ Ratio = \frac{P_2}{P_1} = \sqrt{14}$

$$Expansion\ Ratio = \frac{P_6}{P_7} = \sqrt{9}$$

At Inlets: $T_1 = T_3;\ h_1 = h_3\ and\ T_6 = T_8;\ h_6 = h_8$ (Refer to Figure1)

At Inlets: $T_2 = T_4;\ h_2 = h_4\ and\ T_7 = T_9;\ h_7 = h_9$

- $T_1 = 295K$
  $h_1 = 295.17\ kJ/kg$

  $T_2 = 429.36K$
  $h_2 = 430.78\ kJ/kg$

- $T_6 = 500K$
  $h_6 = 503.02\ kJ/kg$
  $P_{r6} = 8.411$

  $T_7 = 366.54K$
  $h_7 = 367.18\ kJ/kg$

- $w_{compressor} = 2(h_2 - h_1) = 2(430.78 - 295.17) = 271.22\ kJ/kg$
- $w_{turbine} = 2(h_6 - h_7) = 2(503.02 - 367.18) = 271.68\ kJ/kg$
- $w_{net} = 271.68 - 271.22 = 0.46\ kJ/kg$
- $q_{in} = (h_6 - h_4) + (h_8 - h_7) = 72.24 + 135.84 = 208.08\ kJ/kg$
- $W_{net} = \dot{m}(w_{net}) = 0.20(0.46) = 0.092\ kW/s = 331.2\ kW/h$
- Requirement= *320.8 kW/h*

4) Thermal Efficiency

- $\eta = \frac{w_{net}}{q_{in}} = \frac{0.46}{208.08} = 0.0022$

5) Back Work And Pressure Ratios

- $BWR = \frac{W_{turb} - W_{net}}{W_{turb}} = \frac{271.68 - 0.46}{271.68} = 0.998$
- $P_{r1} = 1.3068$
- $P_{r2} = \sqrt{14} \times 1.3068 = 4.89$
- $P_{r6} = 8.411$
- $P_{r7} = \frac{1}{\sqrt{9}} \times 8.411 = 2.80$

B. Non-Ideal Regenerative Brayton Cycle

1)T-s Diagram

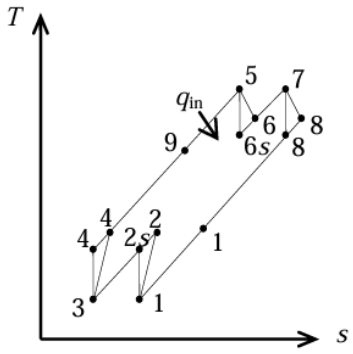


Figure 4:T-s Diagram Of Non ideal, regenerative Brayton Cycle

2) Component Efficiencies and Efficiency Equation Modification

$$\eta_c = \frac{w_s}{w_a} \cong \frac{h_{2s} - h_1}{h_{2a} - h_1}$$

$$\eta_c = 0.70$$

$$\eta_t = \frac{w_a}{w_s} \cong \frac{h_3 - h_{4a}}{h_3 - h_{4s}}$$

$$\eta_t = 0.75$$

$$Compressor\ Inlet = T_1 = 295K$$
$$Turbine\ Inlet = T_6 = 500K$$
$$Compression\ Ratio = \frac{P_2}{P_1} = \sqrt{14}$$
$$Expansion\ Ratio = \frac{P_6}{P_7} = \sqrt{9}$$

At Inlets: $T_1 = T_3;\ h_1 = h_3\ and\ T_6 = T_8;\ h_6 = h_8$

At Inlets: $T_2 = T_4;\ h_2 = h_4\ and\ T_7 = T_9;\ h_7 = h_9$

- $T_1 = 295K$
  $h_1 = 295.17\ kJ/kg$
  - $P_{r2} = \sqrt{14} \times 1.3068 = 4.89$
  - $T_2 = 429.36K$
  - $h_2 = 430.78\ kJ/kg$
  - $0.70 = \frac{430.78 - 295.17}{h_{2a} - 295.17}, h_{2a} = 488.9 kJ/kgK$

- $T_5 = 950K$
  - $h_5 = h_7 = 989.225\ kJ/kg$
  - $P_{r5} = 93.14$
  - $P_{r6} = \frac{1}{\sqrt{9}} \times 93.14 = 31.04$

- $T_6 = 719.26K$
- $h_6 = 728.37\ kJ/kg$
- $0.75 = \frac{989.225-728.37}{989.225-h_{6a}}, h_{6a} = 793.58\ kJ/kgK$

- $w_{compressor,ideal} = 2(h_{2a} - h_1) = 2(488.9 - 295.17) = 387.46\ kJ/kg$
- $w_{turbine,ideal} = 2(h_5 - h_{6a}) = 2(989.225 - 793.58) = 391.29\ kJ/kg$
- $w_{net} = 391.29 - 387.26 = 3.83\ kJ/kg$
- $BWR = \frac{W_{comp}}{W_{turb}} = \frac{387.26}{391.29} = 0.99$
- $q_{in} = (h_5 - h_4) + (h_7 - h_6) = 500.325 - 195.645 = 301.68\ kJ/kg$
- $\eta = \frac{w_{net}}{q_{in}} = \frac{3.83}{301.68} = 0.0126$
- $q_{regen} = \varepsilon(h_8 - h_4) = 0.70(793.58 - 488.9) = 213.276\ kJ/kg$
- $q_{in,new} = q_{in,old} - q_{regen} = 301.68 + 213.276 = 88.4\ kJ/kg$
- $\eta_{regen} = \frac{w_{net}}{q_{in,new}} = \frac{3.83}{88.4} = 0.043$

III. EXPLANATION FOR DESIGN PROCESS

While the report focuses on implementation of adequate Brayton Cycle for power plant capable of generating the said amount of energy by implementing Brayton's Cycle.

A. Appropriate Assumptions and Justifications:

1. ***Ideal vs. Non-ideal Cycles:***

Assumption: The analysis considers two scenarios:

Ideal Brayton Cycle: This is a theoretical model with perfect component efficiencies (compressors, turbines, regenerator) to represent the maximum achievable efficiency under ideal conditions.

Non-ideal Regenerative Brayton Cycle: This is a more realistic model that considers actual component efficiencies (around 75%) and a 70% effective regenerator.

Justification: This approach allows for two key benefits:

Benchmarking: The ideal cycle represents a theoretical best-case scenario, providing a benchmark for the maximum achievable efficiency.

Real-World Relevance: The non-ideal cycle with realistic component and regenerator effectiveness reflects the limitations of real-world systems, offering a more accurate assessment of the system's actual performance in practice.

2. ***Building Parameters:***

Assumption: Specific details about the building are used, such as:

- **Dimensions (floor area and height):** Knowing the volume of air to be heated is essential for calculating the required heating capacity. (3969 m^2 being the area for floor and the height being 3m)
- **Occupancy (number of people):** The number of occupants directly impacts the internal heat generation due to body heat, influencing the heating demand.
- **Window Properties (size and material):** Window size and material (double-glazed) affect heat transfer through the windows. This helps determine how much heat escapes or enters the building due to sunlight.

Justification: These details are crucial for accurately calculating the heating demand the waste heat from the power generation system needs to address. Precise heating demand ensures efficient waste heat utilization and avoids over or under-heating the building.

3. Climate Data & Internal Heat Sources:

Assumption:

- **Climate:** Average daytime temperature in Lahore and the desired indoor temperature are used.
- **Internal Heat Sources:** Occupant count and typical power consumption of lighting and equipment are assumed to estimate the internal heat generation within the building.

Justification:

- **Climate:** This data helps determine the heat transfer through the building envelope (walls, windows, roof) due to the temperature difference between inside and outside. This directly impacts the heating needs, especially during colder months.
- **Internal Heat Sources:** Assuming a typical number of occupants and their energy consumption from lighting and equipment helps estimate the internal heat generated within the building. This internal heat generation contributes to the overall heating needs and reduces the amount of external heating required.

4. ***Ventilation Rate:***

Assumption: A standard air change rate is used to account for the heat exchange that occurs when fresh air replaces stale air inside the building.
Justification: Ventilation plays a role in heat loss during cold weather. Including a standard air change rate provides a reasonable estimate of this heat loss and helps determine the overall heating needs of the building.

5. ***Limitations and Further Refinement:***

While these assumptions are justified for initial design purposes, for a real-world implementation, it's recommended to gather more detailed data on:
Occupant behavior patterns: Knowing working hours and activity levels can help refine the internal heat generation estimates.
Equipment usage patterns: Actual power consumption data for equipment can provide a more precise picture of internal heat generation.
Real-time weather data: Accounting for variations in temperature throughout the year allows for a more dynamic and adaptable heating strategy.
By incorporating this more detailed information, the design can be further optimized for efficiency, performance, and occupant comfort.

B. Rationalization for Intercooling and Heating

The report proposes a modified Brayton cycle with two stages of intercooling and reheating to achieve several advantages. Let's delve deeper into the reasons behind this choice:

1. Reduced Compression Work:

Concept: In a standard Brayton cycle, compressing air to a high pressure significantly increases its temperature. This hot air requires more work for further compression in the subsequent stage.
Intercooling's Role: Intercooling introduces a heat exchanger between compression stages. This cools down the air after the first compression stage before it enters the second stage.
Benefit: By starting with cooler air in the second stage, less work is needed to achieve the final desired pressure. This translates to a reduction in the overall compression work required, leading to higher efficiency for the entire cycle.
Analogy: Imagine inflating a balloon. It's much easier to inflate a cool balloon compared to a hot one that's already expanded due to trapped heat. Similarly, intercooling allows us to "work with cooler air" in the second compression stage, requiring less effort.

2. Increased Turbine Work Output:

Concept: In a standard Brayton cycle, the hot compressed air expands through the turbine, generating work. However, the exhaust from the turbine still contains significant thermal energy.
Reheating's Role: Reheating introduces a heat source between the turbine stages. This reheats the air exiting the first turbine stage before it enters the second turbine stage.
Benefit: By reheating the air, we increase its temperature again. Hotter gas expands with more force, allowing the second turbine to extract more work from the expanding gas. This results in a higher overall power output from the cycle.
Analogy: Think of a steam engine. Hotter steam pushes the pistons with greater force, generating more power. Reheating the air in the Brayton cycle plays a similar role by providing a hotter working fluid for the second turbine stage.

3. Improved Thermal Efficiency:

Combined Effect: By reducing compression work (point 1) and increasing turbine work output (point 2), the combination of intercooling and reheating offers a significant advantage.
Efficiency Gain: The decrease in compression work relative to the increase in turbine work output translates to a substantial improvement in the overall thermal efficiency of the power generation cycle.
Practical Benefit: Improved thermal efficiency means the system produces more power while consuming less fuel. This translates to cost savings on fuel and reduces the environmental impact of the power generation process.

4. Waste Heat Utilization for Building Heating:

Waste Heat Potential: The exhaust gases exiting the turbine, even after reheating, still contain significant thermal energy. This heat is typically wasted in conventional power plants.
Waste Heat Recovery: In this design, a heat exchanger can be used to capture this waste heat from the exhaust gases.
Building Heating Application: The captured heat can then be used to meet the heating needs of the office building, especially during colder months in Lahore.
Synergy: This approach not only reduces the need for a separate heating system but also improves the overall system's efficiency by utilizing waste heat as a valuable resource.

Justification for This Approach:

While intercooling and reheating add complexity to the system with additional heat exchangers and potentially higher maintenance needs, the potential benefits outweigh the drawbacks in this specific application. Here's why:
Focus on Efficiency: The primary goal is to create a power generation system that is efficient and minimizes fuel consumption. Intercooling and reheating significantly contribute to achieving this goal.
Waste Heat Potential: Lahore experiences colder months where there's a demand for building heating. The ability to utilize waste heat for this purpose makes the system more sustainable and reduces the overall energy consumption of the building complex.
In conclusion, the use of intercooling and reheating in this modified Brayton cycle offers a compelling solution for this specific application. It prioritizes efficiency, reduces fuel consumption, and leverages waste heat as a valuable resource to meet the building's heating needs.

IV. IDENTIFICATION OF MISSING ELEMENTS

While the report provides a good foundation for the design, there are some key elements that require further consideration for a complete real-world implementation:

- **Detailed System Design:** The report outlines the theoretical concept using a Brayton cycle with intercooling and reheating. However, a detailed engineering design is needed. This would include specifications for components like compressors, turbines, heat exchangers, and the regenerator.
- **Control System Design:** A control system is crucial for regulating various aspects of the power generation system, such as maintaining optimal operating pressures and temperatures, managing intercooling and reheating processes, and ensuring efficient waste heat recovery.
- **Economic Analysis:** An economic feasibility study is necessary to assess the initial investment costs, ongoing maintenance costs, and potential fuel savings compared to traditional power generation methods. This will help determine the payback period and overall economic viability of the system.
- **Environmental Impact Assessment**: An environmental impact assessment should evaluate the potential environmental benefits (reduced fuel consumption) and any potential drawbacks (emissions, noise) associated with the proposed system.
- **Safety Considerations:** A thorough safety analysis is essential to identify potential hazards associated with the system, such as high-pressure components, hot exhaust gases, and noise levels. This will guide the implementation of safety measures to mitigate these risks.

V. REALISTIC CONSTRAINTS

Several real-world constraints need to be factored into the final design and implementation:

- **Component Availability:** The availability and cost of specific components like high-efficiency compressors, turbines, and a reliable regenerator need to be considered.
- **Space Limitations:** The physical space available within the building will dictate the layout and footprint of the power generation system. This might necessitate modifications to the initial design concept.
- **Maintenance Requirements:** The complexity of the system with intercooling, reheating, and waste heat recovery will require ongoing maintenance. The design should consider ease of access for maintenance personnel and potential downtime associated with maintenance activities.
- **Integration with Existing Building Infrastructure:** The power generation system needs to be seamlessly integrated with the existing electrical and heating systems within the building. This might involve modifications or upgrades to the existing infrastructure.
- **Regulations and Permits:** Obtaining necessary permits and complying with local regulations for power generation and waste heat utilization are crucial aspects of the implementation process.

By addressing these missing elements and considering the real-world constraints, the design can be further refined and optimized for a successful real-world application.

distribution.

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