In this study, an indirect burner system for solid biomass fuel is designed. The design is motivated by the need to solve the problem related to a direct burner system, such as slagging and high pollutant emissions due to the high-temperature burning process. Therefore, the utilization of an indirect burner is expected to improve the reliability of the solid biomass combustion process. It also can be used to reduce coal consumption by using an indirect burner where the working fluid reaches a relatively higher temperature before entering the boiler. The design used the first principle method for creating the regenerator heat exchanger. The regenerator consists of a mantle and coil heat exchanger. The test used solid biomass fuel for the combustion process where the working fluid first enters the mantle heat exchanger and then the coil heat exchanger. As a result, the mantle absorbs sufficient heat losses from the combustion chamber with the highest temperature increment of 19 °C. The warm water from the mantle then flows to the coil arrangement within the combustion chamber. As a result, the highest temperature of the coil is 84.5 °C. The heat transfer rate for the coil and mantle is 57.2–85.6 and 124.9–141.5 W. The key finding is that the combined regenerative heat exchanger can deliver a higher transfer rate. This can be achieved since the heat exchanger utilizes the same flow distribution, increasing the mean temperature differences at the inlet. Thus, it can produce an average heat transfer rate of 210.5 W. Therefore, energy consumption for coal or other fossil fuels can be reduced significantly. The data can be used for further improvement of the existing boiler system and help to increase the thermal efficiency of the system

Keywords: biomass, indirect burner, regenerative heat exchanger, regenerator, mantle heat exchanger

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INCREASING THE RELIABILITY OF BIOMASS SOLID FUEL COMBUSTION USING A COMBINED REGENERATIVE HEAT EXCHANGER AS AN INDIRECT BURNER

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1. Introduction

Renewable and alternative energy sources are essential to sustainable development and climate change mitigation. This can be implemented by harvesting wind and solar energy as renewable sources, including biomass as part of alternative energy sources to solve the waste issue [1]. However, the actual implementation of renewable energy is complex since it depends on energy storage, which increases production costs. On the other hand, biomass seems more feasible for large-scale implementation as it is cheaper and can be produced from agriculture by-products and municipal solid waste (MSW) [2]. It is also more profitable since it recognizes regenerative fuel that can be reproduced continuously. This also motivates research to optimize the collection system for waste in cities in order to improve the collection system while reducing the cost of the process [3].

Innovative research such as the gasification process shows a tremendous trend to mitigating two relevant problems: alternative energy sources and waste issues [4]. Syngas production combined with refuse derived fuel (RDF) is very attractive to improve alternative energy utilization [5]. It is also important to support the recent trend in alternative energy utilization to be applied in wider application [6]. Furthermore, the trend in the alternative scheme by using the energy substitute concept is also gaining momentum [7]. It can be applied by using biomass as an accelerator fuel in the boiler system, which helps to minimize the energy consumption in the main burner [8]. The idea is useful, which can meet the criteria for both industrial and residential application. Therefore, the total energy utilization from biomass can be increased significantly, which reduces the consumption of fossil fuel while minimizing the waste problem.

Biomass is an ideal option for regenerative fuel that works as a thermal substitute, especially as a thermal energy source for industrial and household boilers. Thermal substitutes can replace fossil fuel, particularly coal. Therefore, they can be applied for power plants and as alternative thermal sources for residential water and space heating [9]. Using biomass-based solid fuel as a thermal source for the burning process is highly attractive for researchers and industrial practitioners since it has the same function as solid fossil fuel [10]. The recent development focuses on the integration process with the existing system, including optimization to increase the effectiveness of the biomass solid fuel burning process, particularly for industrial and household boilers [11].

Nevertheless, the biomass utilization for an actual system, which requires high specification, is relatively hard. For example, using biomass as an alternative energy source for blast furnaces seems possible but it is hard to control the combustion process [12]. An alternative application for biomass burners is a boiler power plant, which normally uses coal or other fossil fuels [13]. The utilization of biomass for boilers is also interesting as it reduces the net energy consumption of the primary fuel. This can be achieved for the system using indirect alternative heat sources such as a thermal energy storage system [14]. Despite focusing on the biomass source, it is critical to improve the reliability of biomass fuel in an actual system by addressing the fuel burning process. It is well known that the direct combustion process of biomass is complex and not suitable for large power plants. One study considers overcoming NOx emissions from the direct burner system of biomass solid fuel as the impact of the high-temperature burning process by using a catalyst since it can absorb polluting gasses [15].

The high temperature of the burning process in the existing burner causes an increase in emissions for solid biomass fuel [16]. Those problems make the direct burner system uneconomical and reduce the effective energy uptake from solid biomass fuel as an alternative to replace coal for industrial and household boilers for thermal generation [17]. The direct burning process is also not suitable since the feeder system must be modified according to the type and size of solid fuel [18]. Considering the problem, it seems possible to develop an alternative model of a biomass burner to minimize the related issue. Furthermore, the slagging problem for the direct burning process within the combustion chamber occurs as the impact of impurities of solid biomass fuel [19]. Thus, the reliability of the direct combustion burner is undesirable. This makes the fuel substitution between biomass and fossil fuel disadvantageous.

As an alternative, the indirect burner for biomass solid fuel can be designed according to the basic idea of a regenerative heat exchanger. The basic concept of a regenerative heat exchanger or regenerator heat exchanger is the indirect heat exchange process between the working fluid and the thermal source. This means that the working fluid can absorb heat from thermal sources without mixing [20]. The working principle for the regenerator heat exchanger makes it suitable for special-purpose applications and more flexible for complex heat transfer processes like caloric generator systems [21]. The common application for the current technology of regenerator heat exchangers is the thermal energy storage system. The storage material (generally for sensible and latent heat material) is stored within the container and works as a heat exchanger [22].

The key problem is associated with the direct burning process. It is still related to the current development and research for minimizing the impact of the direct burning system as it allows solving the problem of biomass utilization as a solid fuel. Therefore, research related to increasing the reliability of biomass solid fuel combustion is highly relevant and growing.

2. Literature review and problem statement

The use of an indirect burner for biomass solid fuel is attractive as it can improve the reliability of the biomass burner system. This provides better flexibility in the installation process without modifying the existing system and reaches higher energy generation from solid fuel. The basic concept has already been implemented in [23] where the indirect biomass co-firing system is utilized to increase the reliability of the burning system. However, further improvement is still required to allow better flexibility of the application in different fields. For example, applying an indirect burner through the co-firing scheme for an industrial boiler reduces the cost of processing, making it economically feasible. As reported in [24], this method promotes a better processing cost for using biomass in the system by improving the performance of the net energy system. But still, the study was limited to the cost aspect rather than technology development even though it provides a clear basis for further improvement of the indirect burner system for biomass.

Perhaps, the main positive outcome of the co-firing model is for biomass boilers, which can be combined with low-grade coal such as lignite. As reported in [25], the combined effect of the biomass burning system and low-grade coal provides a better energy balance at reduced cost since the system uses a cheaper fuel. This demonstrates that the co-firing concept as well as the indirect burner is suitable from an economic point of view. Regardless of the findings, the concept still uses the same burner mechanism, which can hardly be implemented for small-scale application. Another application for the indirect burner is reported in [26] where the fundamental concept of an indirect burner for the gasification of woody biomass is employed, and it was concluded that the proposed method provides higher thermal efficiency than the direct burner system. Further consideration has also been analyzed according to the technical and economic aspects for using the indirect burner of biomass solid fuel.

In [27], a feasibility study for biomass boilers was conducted, indicating that increasing the feed water system is advantageous for increasing energy efficiency and reducing biomass boiler fuel consumption. This supports the idea that the indirect burner is suitable in terms of both the economic and technological aspects for the existing system. Wider application for the indirect burner is also implemented for a preheating system in hydrogen gas production combined with low-rank coal [28]. The study suggests the potential of decreasing the energy cost for hydrogen production by using biomass solid fuel. However, it focuses on hydrogen production and relies on a large-scale system. One of the advanced utilizations for an indirect burner is reported in [29] as it promotes the indirect burner system, which can be accompanied by a solar heater and thermal energy storage system, making it more feasible for more comprehensive thermal applications.

Focused on the regenerative heat exchange model, which is suitable for small-scale biomass burners, the typical regenerator heat exchanger for thermal storage systems uses coil and mantle arrangement. The coil heat exchanger is stored within the container, increasing the surface area and heat transfer rate. As reported in [30], the use of coil arrangement is also advantageous as it has a larger surface area and a smaller volume, which can increase the stored energy within the container. This promotes a better heat transfer rate of the system and delivers a better net energy transfer. Nevertheless, the coil heat exchanger is applied for the organic Rankine cycle rather than the biomass burner system. Another suitable method for an indirect biomass burner system using the regenerative heat exchanger method is a mantle heat exchanger. As suggested in [31], the mantle heat exchanger reduces the heat losses from the system and extracts heat from the body of the heat source for further utilization. However, the study focuses on the case study of a solar heater system.

As mentioned above, the co-firing method and the indirect burner are suitable for increasing the reliability of biomass solid fuel combustion. The method of regenerative heat exchanger is suitable for the indirect burner system. It is necessary to develop a regenerator heat exchanger, which can be specifically implemented in an indirect burner system for increasing the reliability of the biomass solid fuel combustion system.

3. The aim and objectives of the study

The aim of the study is to promote better biomass solid fuel utilization using a regenerative heat exchanger as the concept of an indirect burner system. This will improve the reliability of biomass solid fuel and eliminates the related problem in the direct burner system.

To achieve this aim, the following objectives are accomplished:

– to determine the temperature profile of the working fluid on the mantle side under different working conditions;

– to determine the temperature profile of the working fluid on the coil side under different working conditions;

– to analyze the heat transfer rate of the system under different working conditions.

4. Materials and methods

The key point of the study is extracting heat from the burning process of solid biomass fuel. The extracted heat is absorbed by the working fluid (water) where the working fluid flows within the channel and does not mix with the heat sources. Thus, the main function of the burner can be focused on the heat transfer rate. The absorbed heat from the burning process is relatively complex, particularly for involving the fluid flows within the channel. For simplification, the heat transfer rate and the extracted heat from the burning process can be measured based on the temperature differences between the inlet and outlet ports of the working fluid.

The study uses the design concept of the first principle method, which started with evaluating the key components and preliminary design to achieve the goal [32]. The key point of a regenerative heat exchanger is the ability to absorb thermal energy effectively from thermal sources, which can be done using an appropriate heat exchanger [33]. The coil arrangement is proven to meet the criteria of a regenerative heat exchanger, particularly for the system that uses active thermal sources like a burner and thermal energy storage system [34]. Considering the success story of coil arrangement for regenerator heat exchangers, the present study utilizes the same model in the combustion chamber. As mentioned before, the proposed design also employs a mantle heat exchanger installed in the combustion chamber's outer area to absorb the conductive heat losses on the wall. The absorbed heat from the mantle then flows to the coil arrangement. This can help to increase the total absorbed heat from the combustion process, which means better thermal efficiency [35].

Considering all key components and design purposes, we designed the combined regenerative heat exchanger for an indirect biomass burner as shown in Fig. 1. The key components are the coil heat exchanger at the combustion chamber, mantle heat exchanger at the outer side of the burner (combustion chamber), air supply for combustion purpose and fuel feeder. Cold water flows from the inlet at the mantle side. The water absorbs some thermal energy from the burner's outer body and increases the water temperature. The warm water outlet from the mantle is directly connected to the inlet of the coil heat exchanger. It flows directly through the coil heat exchanger within the burner and eventually gets a higher temperature as it absorbs heat from the combustion process. The hot water flows through the outlet, which can be used for several purposes like feed water supply, hot water, and dryer.

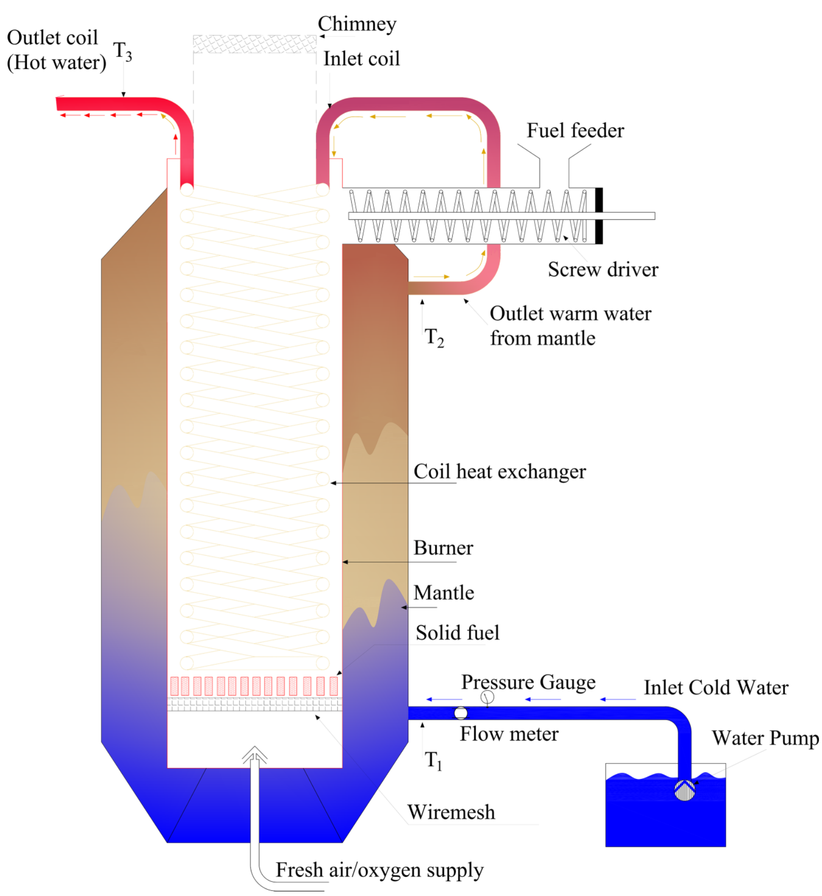


Fig. 1. Basic design of a combined regenerative heat exchanger for an indirect biomass burner and a test apparatus

The coil heat exchanger was designed as a dual coil since it has a better surface area than a single coil arrangement. The height was 37.65 cm, with a diameter and pitch of 10.4 cm and 0.75 cm. The coil was made of copper (ID and OD 0.5 and 0.61 cm), and the number of turns was 50. All dimensions are given in [36]. The void volume of the mantle side is approximately 1,059 cm^3. The inner diameter of the water tube for the mantle side is 0.5 cm. The experimental test was conducted using solid fuel (with a heating value of 14.2 MJ/kg). The test was conducted for 60 minutes using two scenarios: standard air and oxygen combustion. The mass flow of the water is set at three different values: 5, 10 and 15 g/s. The purpose of using different air supply and mass flow is to evaluate the overall performance of the designed indirect burner and evaluate the operation of the regenerative heat exchanger. By using multiple scenarios, it is expected to obtain the natural operation of the regenerative heat exchanger for the indirect burner.

Three thermocouples (type K) were used for the test. The inlet temperature of the water was kept constant at 19 °C and measured by T_1. The water flow was monitored through a flow meter and a pressure gauge. The water pressure was set at 2 bar. The water absorbs heat from the combustion chamber body. The output temperature of the mantle side was measured through T_2. The warm water flows through the coil arrangement and is heated by the combustion process inside the combustion chamber. The temperature increment from the coil was measured by T_3. The heat transfer rate from the mantle side can be analyzed precisely by using the temperature differences between T_1 and T_2, while the heat transfer rate from the coil side was analyzed by observing the temperature difference between T_2 and T_3. The standard air combustion was done by supplying fresh air from a compressor at an average pressure of 3 bar. During the oxygen combustion process, pure oxygen was supplied from an oxygen tank at a pressure of 3 bar.

5. Results of a combined regenerative heat exchanger for a biomass burner

5. 1. Results of the temperature profile of the working fluid on the mantle side under different working conditions

The experiment was conducted continuously to observe the temperature profile and trendline at the mantle and coil during the combustion process. Fig. 2 presents the temperature profile on the outlet of the mantle side (T_2) during the standard air combustion process. As can be seen, the change in the mass flow of the working fluid affects the heat absorption during the test, which can be observed based on the outlet temperature of the fluid. According to the results, a lower mass flow rate for the mantle can promote a higher temperature, indicating a sufficient heat exchange process. The mass flow of 5 g/s shows an accelerated temperature increment up to 32.7 °C after 8 minutes (Fig. 2, *a*). The trendline reveals the limitation of the temperature increment with non-linear correlation (Fig. 2, *b*). This is acceptable for the actual heat transfer process since the convective heat transfer has a certain working boundary and limitation due to the turbulence effect during the heat exchange process.

The oxy-combustion process provides a better exothermic process of fuel, which helps to release a higher amount of thermal energy. This can be observed clearly in the trend of increment of the outlet temperature of the mantle heat exchanger, which is higher than in the standard air combustion process. As shown in Fig. 5, *c*, the highest temperature from the mantle side is obtained at 39 °C for a mass flow rate of 5 g/s. However, higher thermal release from the burner increases the burner's surface temperature and reduces the heat transfer rate at the mantle side with a higher mass flow rate. This also can be observed from the temperature trendline (Fig. 3, *b*), where the gap between the mass flow rates of 5, 10 and 15 g/s increases. A high mass flow rate reduces the retention time within the mantle, slowing the heat exchange process between the outer surface of the burner and the working fluid. This also corresponds to the interaction between the working fluid and the combustion chamber wall, which creates a surface boundary under a high mass flow rate. Consequently, water cannot absorb heat from the wall effectively.

As expected, the mantle heat exchanger can absorb sufficient heat from the combustion chamber wall. The temperature increment, both for standard air and oxygen combustion, indicates a trendline where the working fluid can reach a relatively higher temperature. This implies that the heat, which is supposed to be thermal losses from the burner, can be absorbed by the working fluid. Therefore, the role of the mantle heat exchanger is to reduce the possibility of thermal losses from the system.

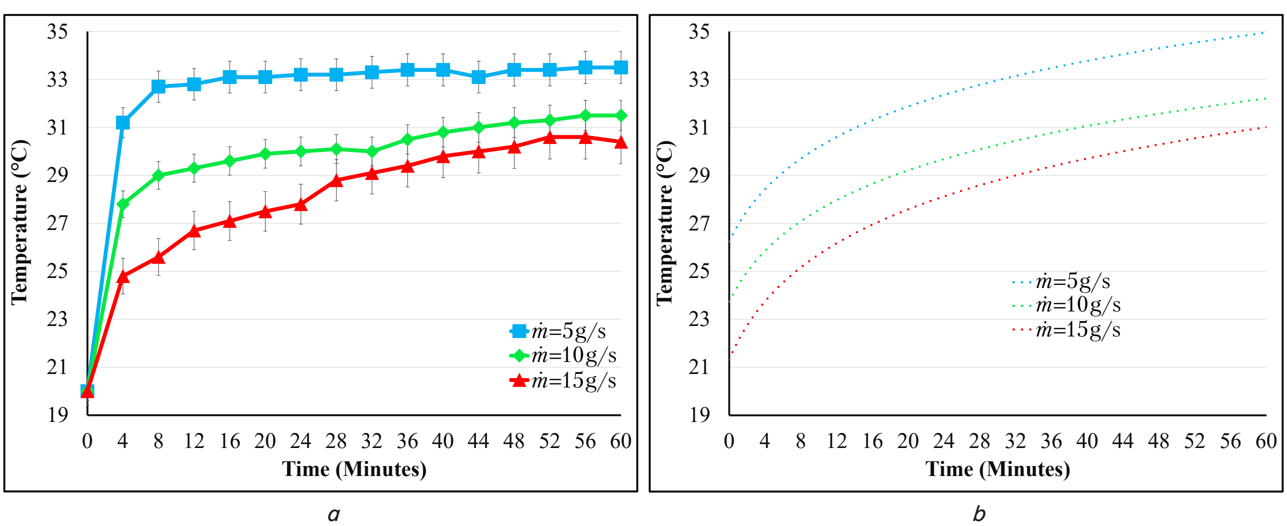
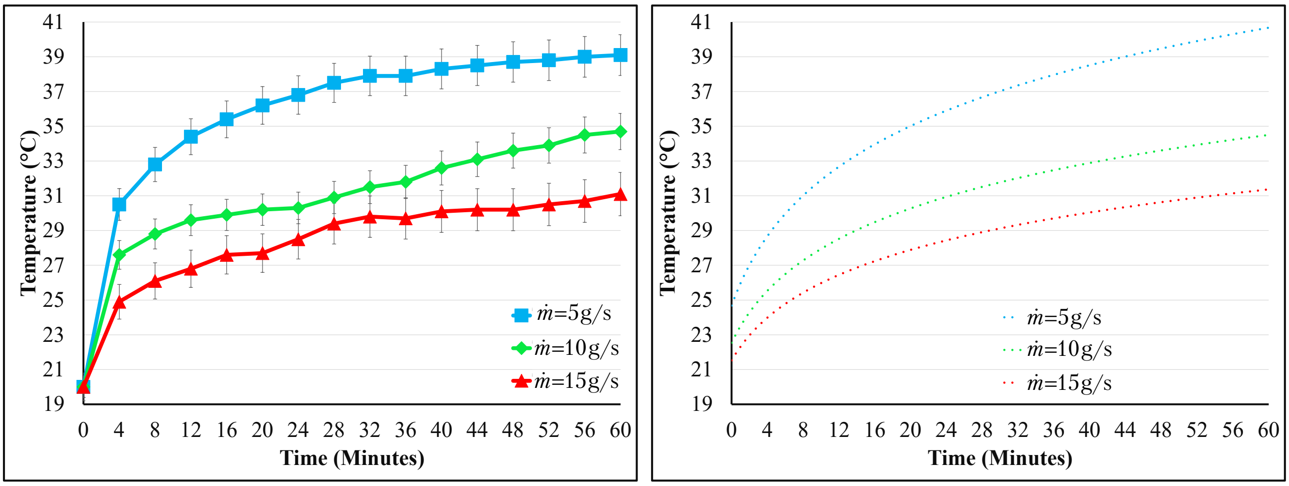


Fig. 2. Performance at the mantle side with different mass flow rates under standard air combustion: *a* — temperature profile; *b* — logarithm trendline



a *b*

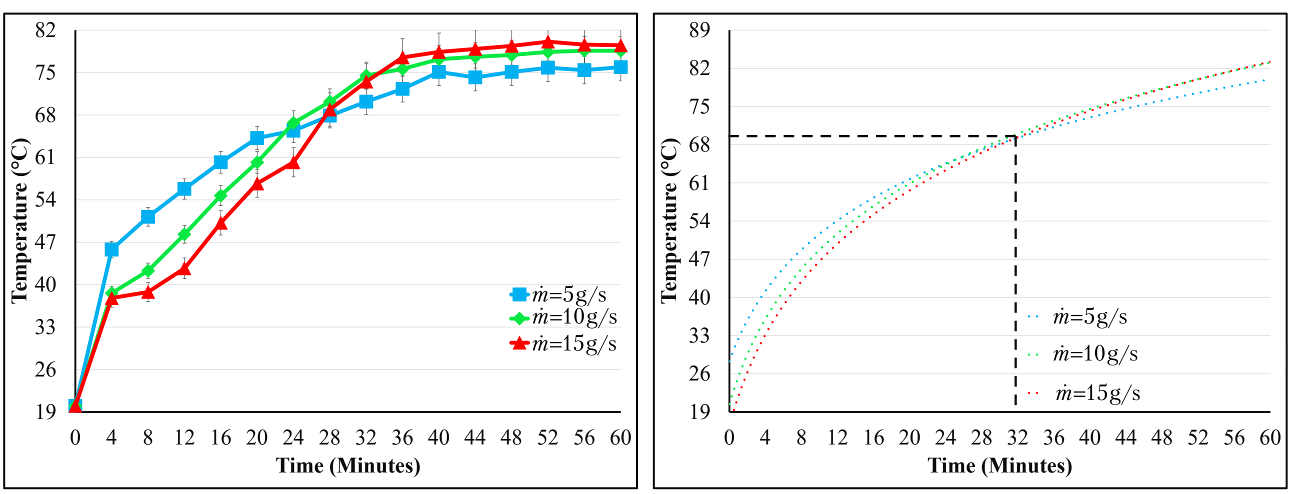
Fig. 3. Performance at the mantle side with different mass flow rates under pure oxygen combustion: *a* — temperature profile; *b* — logarithm trendline

5. 2. Results of the temperature profile of the working fluid on the coil side under different working conditions

Fig. 4, *a* presents the outlet temperature of the coil heat exchanger. It can be observed clearly that the effect of mass flow rate for the coil heat exchanger is quite distinctive from the mantle side. The highest temperature is reached at a mass flow rate of 10 and 15 g/s after 60 minutes. Despite that, the initial temperature increment for both mass flow rates is relatively low compared to the mass flow rate of 5 g/s. The main reason for this condition is a lower temperature input from the mantle heat exchanger. This slows down the temperature increment in the coil heat exchanger. At a lower mass flow rate, the outlet temperature from the mantle side is relatively high, which helps to achieve a higher temperature for the water after passing the coil side. The cut-off line (dashed line in Fig. 4, *b*) for the mass flow rate is obtained after 32 minutes at a temperature of 69 °C. This indicates that all mass flow rates can achieve the same temperature. As the combustion process continues, the temperature tends to increase by using a higher mass flow rate while an unsubstantial increment occurred for a mass flow rate of 5 g/s.

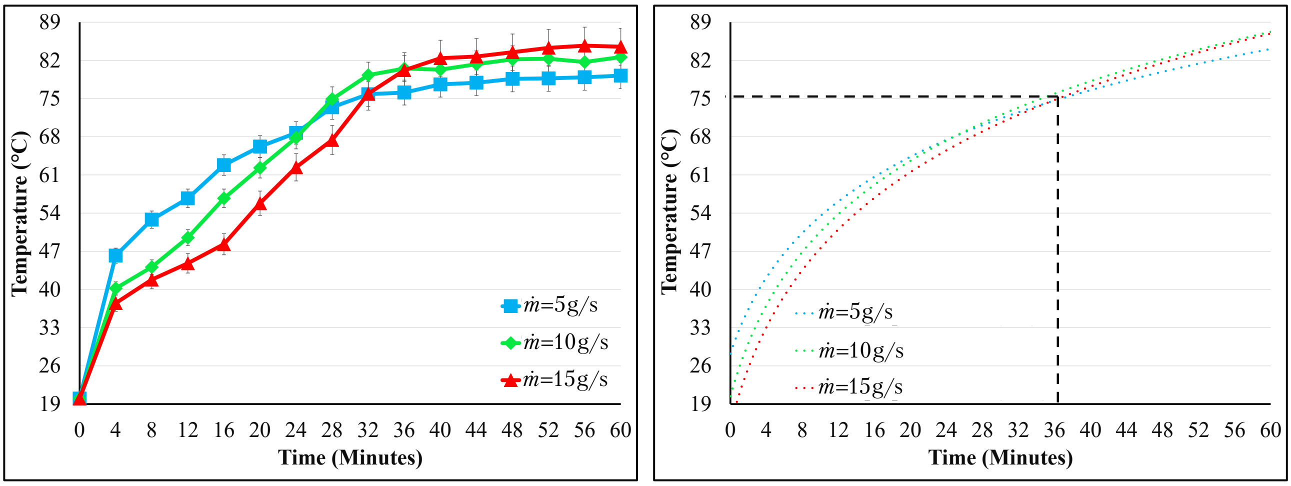
During the oxy-combustion process, the same phenomenon is observed for the coil heat exchanger (Fig. 5). A higher mass flow rate initially has a slow temperature increment and gets higher after sufficient time. The cut-off line is obtained at a relatively higher temperature of 75 °C after 36 minutes. Combustion with oxygen delivers a better exothermic process, increasing the burner's average temperature. This makes the coil's average outlet temperature higher than with standard air combustion. Furthermore, using a double helical coil allows the water to absorb sufficient thermal energy. This makes the final temperature of the coil heat exchanger higher than in the mantle.

Both measurements indicate that the working fluid can achieve a higher temperature after passing the coil heat exchanger. This can be noted as the combined effect of a higher inlet temperature and also a large surface area at the burner side. This increases heat absorption as the working fluid flows within the tube where the tube is heated directly from the burner. Thus, the outlet temperature of the working fluid is high, more than 75 °C for all the scenarios. This demonstrates the fundamental idea that an indirect burner is suitable for raising the temperature of the working fluid before entering the main burner system.



a *b*

Fig. 4. Performance at the coil side with different mass flow rates under standard air combustion: *a* — temperature profile; *b* — logarithm trendline



a *b*

Fig. 5. Performance at the coil side with different mass flow rates under pure oxygen combustion: *a* – temperature profile; *b* – logarithm trendline

5. 3. Results of the heat transfer rate of the system under different working conditions

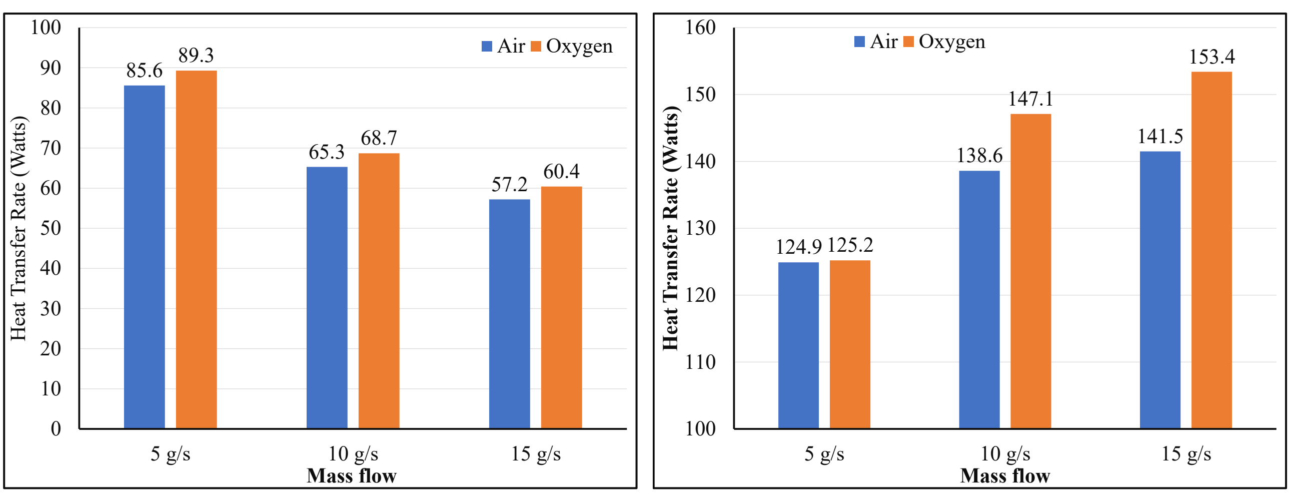
Fig. 6 presents the estimated heat transfer rate for mantle and coil heat exchangers. It can be obtained by considering the heat exchanger's surface area and energy transfer from the burner to the working fluid. The mantle heat exchanger shows that increasing the mass flow rate reduces the average heat transfer rate. Also, the mantle heat exchanger promotes a low transfer rate due to flow distribution within the mantle area. This slows down the heat exchange process for the working fluid and reduces the average heat transfer rate. In contrast, the coil heat exchanger demonstrates a higher outlet temperature since it has a higher heat transfer rate. This can be achieved since the coil is located in the combustion chamber. Furthermore, the coil has a larger surface area, improving the heat transfer rate.

The primary function of both heat exchangers is sufficient. For example, the mantle heat exchanger is designed to absorb heat loss from the combustion chamber. The heat is then absorbed by the working fluid (water) and used as the input for the coil heat exchanger. The coil in the combustion chamber can deliver a higher transfer rate (Fig. 6), which increases the final temperature of the working fluid.

The key point is that the initial temperature of the working fluid, which is relatively high, can minimize the heat losses from the chamber and improve the effective energy uptake from the combustion process. Thus, the working principle for a combined regenerator heat exchanger for an indirect burner is sufficient to meet the feed water supply criteria for industrial boiler systems or water and space heating for residential applications.

6. Discussion of the results of a combined regenerative heat exchanger for a biomass burner

A regenerative heat exchanger works differently compared to a common heat exchanger such as shell and tube since it does not involve two or more working fluids for the heat exchange process. This makes the regenerative heat exchanger suitable for use in the burning system. The characteristic of temperature increment indicates a suitable heat transfer process of the tested mantle regenerative heat exchanger (Fig. 2). Oxygen boosts the combustion process within the burner, which can be indicated by a faster temperature response and the final temperature of the working fluid after passing the mantle heat exchanger (Fig. 3).



a *b*

Fig. 6. Average heat transfer rate: *a* – mantle; *b* – coil heat exchanger

The advantage of using a mantle heat exchanger can be observed distinctively as it can absorb the heat from the combustion chamber wall. Compared to the passive thermal insulation method, implementing a mantle is more suitable as it allows the reuse of heat from the burner, which technically can be considered as an extra heat supply. Thus, the energy balance of the system can be improved significantly.

The coil heat exchanger is located within the combustion chamber, which means that it has direct contact with the heat source. This leads to a rapid increase in the final temperature of the working fluid. It is also affected by the surface area of the coil, which accelerates the heat exchange process from the thermal source to the working fluid. This can be seen in Fig. 4 and Fig. 5 where the final temperature of the working fluid is relatively higher than the final temperature from the mantle heat exchanger. The presence of oxygen during the oxy-combustion process also accelerates the temperature increment of the system, particularly for the coil heat exchanger. Oxygen promotes a better exothermic process during combustion, which helps the fuel burn perfectly and liberate energy more sufficiently. The input temperature from the mantle heat exchanger helps to maintain the final temperature of the burner after passing the coil with a value of more than 75 °C.

The effect of mass flow rate can be observed from the heat transfer rate of each model of the heat exchanger. The mantle heat exchanger shows a better performance at a low mass flow rate where the coil heat exchanger shows the opposite outcome. Even though each model differs relatively, the combined effect of the mantle and coil improves the quality of the heat transfer rate from the system, which provides effective heat absorption from combustion. With a higher temperature at the outlet port (from the coil heat exchanger) and a better combustion process, the indirect burner is highly recommended for implementation in the boiler system. The fuel consumption for the main boiler can be reduced with the help of an indirect burner, which uses biomass. It is also possible to support the system without additional components or modifying the existing system. The proposed concept is expected to be considered as an ideal method with a positive impact in alternative energy source utilization.

However, there are still limitations in this study. The proposed design focuses on the heat exchanger model and heat transfer evaluation, without considering the outlet port for ash removal after the combustion process. Also, the designed chimney has not included a catalytic converter for minimizing pollutant emissions from the combustion chamber. Furthermore, the fouling factor from the combustion process will appear after a certain operation and should be taken into account during the design process, particularly for considering the operation & maintenance (O&M) scenario. Therefore, further improvement is needed by focusing on the design of the outlet port from the combustion chamber as well as adding exhaust gas treatment for minimizing pollutants from the combustion process and analyzing the effect of the fouling factor on the actual operation.

7. Conclusions

1. The maximum temperature difference for the mantle side is obtained at 19 °C where a lower mass flow rate allows maximizing the heat exchange process of the working fluid.
2. The coil heat exchanger can absorb sufficient heat where the maximum temperature increment is obtained at 84.5 °C and shows a better heat exchange process under a higher mass flow rate.
3. The heat transfer rate for both heat exchangers indicates sufficient heat absorption with an average power ranging from 57.2–85.6 and 124.9–141.5 W for mantle and coil heat exchangers.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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