A novel direct-fired porous-medium boiler

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Abstract. Nowadays, power and heat generation systems pay an important role in all economic sectors. These systems are mainly based on combustion reaction and operated under the second law of thermodynamics. A conventional boilers, a main component of heat and power generators, have thermal efficiency in the range of 70 to 85%, mainly owing to they have flue gas heat loss. This paper proposes a novel type of boiler, called a Direct-fired Porous-medium Boiler (DPB). Due to being operated without flue gas heat loss, its thermal efficiency cloud be approximately close to 100%. The steam produced from the proposed boiler; however, is not pure water steam. It is the composite gases of steam and combustion-product-gases. This paper aims at presenting the working concept and reporting the experimental results on the performance of the proposed boiler. The experiments of various operating parameters were performed and collected data were used for the performance analysis. The experimental results demonstrated that the proposed boiler can be operated as well as the conceptual design and then it is promising. It can be possibly further developed to be a high efficiency boiler by means of reducing or suppressing the surface heat loss with better insulator and/or refractory lined.

1. Introduction
The energy and environmental issues become the most serious problem of all lives on the earth and it also keeps on dramatically increasing and will not be remedied easily. One of the best ways to overcome aforesaid problems is utilization of renewable energy via the high efficiency systems with environmental friendly processes [1, 2].

Up to the present day, there are three main types of typical boiler designs: fire tube, water tube and tubeless boilers. These can be deeply classified as: fire tube, vertical tubeless, electric, water tube, cast iron and copper fin types. Currently, boilers are manufactured in many different sizes and configurations depending on the fuel used, specified steam output, and required emissions levels. Inside these boiler (excludes electric one), the combustion or oxidation process is taken place, oxygen (from supplied air) reacts with carbon, hydrogen, and other elements in the fuel to generate a flame and hot combustion gases. These hot gases are drawn for one pass or multi-pass through the boiler. Regarding all of the aforesaid boilers, heat is transferred indirectly to water via conduction through surface or wall. Eventually the hot combustion gases flow through a stack and into the atmosphere. To obtain higher efficiency, the components of boiler are designed to promote efficient combustion, heat transfer and control emission. Literatures revealed that a substantial amount of energy is wasted through high temperature flue gas of the boiler. In typical boilers, an economizer might have conducted for a large size boiler with higher investment cost. At their flue gas temperature ranges from 150 to 250 °C, their thermal efficiency is in the range of 70 to 85% [3, 4]. In addition, nowadays, the environmental issues:
global warming, climate changing and serious disasters are mainly attributed to the combustion of such systems and these serious problems must be overcame as soon as possible.

From the literature, there are many works regarding the industrial, commercial, and institutional boilers (ICI boilers). It can be summarized that no one has proposed about this novel concept of boiler, called a ‘Direct-fired Porous-medium Boiler’ (DPB), as review reported in [5]. It should be noted that, there are some differences between the proposed boiler and the conventional boilers (includes tubeless boiler), such as: no flue gas, no stack, direct heating process without effective wall/surface between hot combusted gases and water, and porous medium (PM) is used for enhancing the heat transfer and recovery. Regarding the PM application in boiler, system, there are very few researches about this, as in [6] and still studied on a laboratory-scale test. It can be expected that this study will full-fill the aforesaid research gap.

With the rational hypothesis and expected performance, the proposed DPB might outperforms the conventional one with many expected advantages, such as:

- High thermal efficiency, the flue gas loss is suppressed
- It is compact in construction, directly heating and mixing without barrier surface
- It requires short time for rising steam, the required residual water for operation is quite small
- Low surface heat loss, with water jacket and lesser outer surface area
- Low emission and particulate matter, more uniform temperature and mixed with water vapor
- Higher superheated temperature, with a compact PM super-heater
- Safety, low amount of hot residual liquid water and no flame to wall contact problem
- High dryness fraction, direct heating with controlled water feed rate
- No stack and economizer, combustion gases mixes and leaves as useful high temperature mixture
- Can be possibly developed for a novel internal combustion steam engine
- Low cost, not complicate, etc.

This current paper aims to presents the working concept of DPB and reports the experimental investigation on its performance to assessing the development feasibility of this new porous burner boiler concept, as the above expected features.

2. Working concept of a novel DPB

The proposed DPB is a double-walled reactor with water jacket, as shown in figure 1. The main different between DPB and conventional boiler is that the hot combustion gasses and the produced steam are mixed and heated before leaving as the useful thermal fluid without flue gas loss. To achieve this novel concept, the porous medium and pressurized flame are conducted.

The working concept of the DPB can be explained as the following 4 steps:

1) There are two exit pipes with two stop valves: bigger stop-valve (V1), for flue-gas or wet steam and smaller stop-valve (V2), for superheated composite-gas. During the cold starting step, these valves must be opened to permit the flue gas easily exit the confined vessel. After the fuel and air are mixed and supplied to the pressurized combustor, the fuel-air mixture will be ignited by a spark plug and the pressurized flame will be taken place inside the combustion chamber. The combustion chamber is partitioned or allocated by the porous medium matrix. This porous medium matrix will act as an ‘optical thermal wall’ to keep the proper condition for a sustainable combustion under higher pressure and moisture condition than usual.

2) After the porous medium is heated as much as possible (depends on the melting point of porous medium used), this heat will be transferred from flame to water inside the water jacket effectively via porous medium. After the water temperature inside the water jacket (T3 as shown in figure 2) reached the saturated temperature at any required steam pressure, then open a vapor feed control valve (V3) while a liquid feed control valve (V4) must be closed. The feed water pump will be turned on whenever the water level is lower than the set lower level, to maintain the constant water level. During this step, V4 may be opened to increase the steam generation rate. This wet steam (at about 1atm) will mix with the combustion hot gases, form more dry steam,
and exit through V1. This composite gases (CG) of steam and combustion hot gasses can be utilized as the useful thermal fluid suitable for indirect heating processes.

3) To get the high pressure superheated CG, V3 and V4 have to be closed. The water-jacket pressure and temperature will be increased. When this pressure reach at about the required steam pressure, which can be seen at the water-jacket pressure gage (P1), then V1 must be closed and V3 must be opened. The wet steam and hot gases are mixed together at the upper region of boiler, far from the optical thermal wall, therefore the steam or moisture will not disturb the flame stability. Finally, the CG are forced to flow through the counter-flow helical coil super-heater and exit the boiler through V2 as the useful superheated thermal fluid suitable for indirect heating processes or power generation at high steam pressure.

4) The steam pressure depends upon the steam consumption rate and fuel-air mixture feed rate or combustion rate. For the steam consumption rate, V2 can be adjusted for the individual boiler test. The combustion rate will be controlled to conserve the constant steam pressure. This combustion rate control may be achieved by two methods: a) a single combustor with motorized flow rate control valves of fuel and air, and b) multi-combustor with pressurize pilot flame and combustor on-off control.

**Figure 1.** The working concept of a Direct-fired Porous-medium Boiler (DPB).
3. Experimental setup
To assess the feasibility of the proposed system practicality, the prototype of DPB was fabricated and tested. In this study, the 25kg metal hex nuts were used as the porous medium, with the porous medium thickness (‘L’ as shown in figure 1) of 7 cm. Figures 2 shows a schematic diagram and photo of the experimental setup used in this study. The experimental setup was designed, concerning the three-phase heat transfer mechanism, to allow the gas and liquid flow in and out of the system to be controlled and measured. In this feasibility test, the flow rate and pressure were controlled manually so that operation over a range of power heat input can be explored. To maintain the constant combustion rate, the LPG and air flow rates were manually controlled for all over the experiments. All temperatures were recorded every ten-second intervals via data acquisition (DAQ) system, comprised of a data logger (Datataker, DT605 model) equipped with K-type thermocouples, and computer software for system monitoring. While the flow rate, pressure and feed water consumption rate were manually measured and recorded.

![Figure 2](image)

**Figure 2.** The experimental setup: a) schematic diagram and b) photo of the proposed boiler system.
4. Performance evaluation
For the boiler performance analysis, let us consider the DPB system as shown in figure 1. To simplify the analysis, the following assumptions are made:

1) Performance is in steady state
2) There is only surface heat loss with the natural convection only
3) The insulator surface is at uniform temperature
4) Properties of all working mediums are independent of temperature
5) The fuel is completely combusted inside the boiler
6) No radiating loss occurs from low temperature insulator surface.

To know the efficiency of a general boiler, the ratio of useful heat exported by outlet steam (\( \dot{Q}_u \)) to the total input heat supplied by fuel (\( \dot{Q}_i \)) was calculated as the following equations:

\[
\eta_{boiler} = \left( \frac{\dot{Q}_u}{\dot{Q}_i} \right) \times 100\%
\]  \hspace{1cm} (1)

As same as the other thermal systems, the overall energy balance equation at steady state can be expressed as:

\[
\dot{Q}_u = \dot{Q}_i - \dot{Q}_l
\]  \hspace{1cm} (2)

where
- \( \dot{Q}_u \) = useful heat output [kW]
- \( \dot{Q}_i \) = input heat supplied by fuel [kW]
- \( \dot{Q}_l \) = heat losses [kW]

Owing to the useful heat of the proposed boiler is not exported by the pure steam, but it is the gas mixtures or composite gas of steam and combustion hot gases. Therefore, between the useful heat and heat loss, the later quantity with the above assumptions can then be estimated easier than the former. Then the equation (1) can be rewritten as:

\[
\eta_{boiler} = \left[ \frac{\dot{Q}_i - \dot{Q}_l}{\dot{Q}_i} \right] \times 100\%
\]  \hspace{1cm} (3)

5. Experimental results and discussions
In all experiments, the total input heat supplied by fuel (\( \dot{Q}_i \)) was fixed with the fuel and air volume flow rates of 0.000146 m³/s and 0.00431 m³/s, respectively. To maintain this input heat, these flow rates were controled by manually adjusting the flow control valves every half an hour.

5.1. The proposed boiler without porous medium
The proposed boiler was firstly tested without porous medium. To know whether it can work without porous medium or not. The experimental results show that, during the preheating step, the water temperature increased slowly. After the preheating temperature reached the saturated temperature at the lowest pressure (1atm), the water (vapour) feed control valve (V3) was then be opened. When the steam was fed into the mixing chamber, the pressurized flame cannot be sustainable or it was extinguished by steam. It can be summarized that, without the thermal wall and heat transfer enhancement of the porous medium, the direct fired steam boiler cannot be actually operated.

5.2. The proposed boiler with porous medium
In this first practicality test, the influences of steam pressure (P1 and P2) on the performance of the proposed DPB were mainly taken into account. There are three steam pressures (P2): 1, 1.5 and 2 bar, were used in the experiments. Refer to the graph shown in figure 3 to 8, the water feed control valve

5
(V3) was opened from the seventeenth minute to thirty-seventh minute. Therefore, the DPB was tested for 20 min until it reached around the steady state condition. It was assumed that the input heat supplied by fuel was constant at 13.72 kW. The efficiency of DPB (during the steam generation as shown in figure 4, 6 and 8) was then be estimated using the aforesaid assumptions and equation (3).

Figure 3 shows the temperature profile of the working fluid (T1 to T11) at feed water pressure (P2) of 1 bar (gage). After the preheating step (V1 and V2 were opened), when the water temperature (T3) of water jacket reached more than 123°C, then V1 was closed and V3 was opened. During the steady state condition (from the twenty-seventh minute to thirty-seventh minute), the CG can then be generated from the DPB with the properties of: T6=217°C, P1=0.4 bar (gage). From the graph, it can be demonstrated that the wet steam did not substantially affect on the flame front, the temperature at the porous medium inlet (T10) was constant at about 850°C. At this condition, the steam generation rate of about 18 kg/hr was obtained. Regarding the thermal efficiency, figure 4 shows the efficiency of DPB with respected to input heat of combustion and surface heat loss. With the low cost 10cm-thickness fiberglass insulator and approximated convective heat transfer coefficient (h) of 2.5 W/m²K, the average surface heat loss during the steady state was about 2.24 kW. Finally, the thermal efficiency during the steady state of the proposed DPB was calculated and the average thermal efficiency of 84% was achieved.

Figure 3. Temperature of working fluid at feed water pressure of 1 bar (gage).

Figure 5 shows the temperature profile of T1 to T11 at P2 of 1.5 bar (gage). After the preheating step, when T3 of water jacket reached more than 125°C, then V1 was closed and V3 was opened. During the steady state condition, the CG can then be generated from the DPB with the properties of: T6=215°C, P1=0.6 bar (gage). From the graph, it can be demonstrated that the wet steam not substantially affected on the flame front, the temperature at the porous medium inlet (T10) was constant at about 873°C. At this condition, the steam generation rate of about 19.5 kg/hr was obtained. Regarding the thermal efficiency, figure 6 shows the efficiency of DPB with respected to input heat of combustion and surface heat loss. The average surface heat loss during the steady state was about 0.5 kW. Finally, the average thermal efficiency during the steady state of the proposed DPB was about 97%.
Figure 4. Heat rate and thermal efficiency at feed water pressure of 1 bar (gage).

Figure 5. Temperature of working fluid at feed water pressure of 1.5 bar (gage).

Figure 7 shows the temperature profile of T1 to T11 at P2 of 2 bar (gage). After the preheating step, when T3 of water jacket reached more than 132°C, then V1 was closed and V3 was opened. During the steady state condition, the CG can then be generated from the DPB with the properties of: T6=237°C, P1=1bar (gage). From the graph, it can be demonstrated that the wet steam not substantially affected on the flame front, the temperature at the porous medium inlet (T10) was constant at about 867°C. At this condition, the steam generation rate of about 21 kg/hr was obtained. Regarding the thermal efficiency, figure 8 shows the efficiency of DPB with respected to input heat of combustion and surface heat loss. The average surface heat loss during the steady state was about 4.1 kW. Finally, the average thermal efficiency during the steady state of the proposed DPB was about 70%.
Figure 6. Heat rate and thermal efficiency at feed water pressure of 1.5 bar (gage).

Figure 7. Temperature of working fluid at feed water pressure of 2 bar (gage).

6. Conclusions
A prototype of DPB was fabricated and tested to assess the feasibility of this new type boiler, as the above expected features. The experimental results show that the proposed DPB can be practically operated with high expected performance. It can be said that this innovation can be achieved by using a thermal wall of porous medium. This thermal wall not only maintain the condition for sustainable combustion but it also enhance the heat transfer from the flame to the fed water effectively. Among these three pressures, with the existing components, the proposed DPB should be operated at 1.5 bar (gage) to get the high thermal efficiency of about 97%. With this perspective, it can be concluded that the proposed DPB is promising and can possibly developed to be a high performance actual system for both heat and power generation systems.
Figure 8. Heat rate and thermal efficiency at feed water pressure of 2 bar (gage).

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