The International Journal of Engineering and Science (IJES)
|| Volume || 7 || Issue || 4 Ver. I || Pages || PP 79-83 || 2018 ||
ISSN (e): 2319 – 1813 ISSN (p): 23-19 – 1805

Effect of Contact between Fine Wire Heater and Water-Containing Porous Body on Rapid Generation of Superheated Steam

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---*ABSTRACT*---
We proposed a simple method for the rapid generation of superheated steam using a water-containing porous material. The start-up and cut-off responses are of the second order, and the maximum energy utilization efficiency for input power is very high. Although the contact state between the heater and the water-containing porous body has a great influence on the performance of the rapid superheated steam generator, it has not been clarified yet. Therefore, the effect has investigated experimentally changing the gap between fine wire heater and water-containing porous body in the present paper. As a result, it is found that the response of superheated steam generation is less influenced by the gap between the heater and the water-containing porous body, and the larger the gap, the higher the steam temperature produced.
Keywords*-Porous wick, Rapid vaporization, Steam generator, Super-heated steam*

Date of Submission: 24-03-2018 Date of Publication: Date: 12-04-2018

I. INTRODUCTION

Saturated and superheated steam is often used in home appliances, such as steam irons, steam cookers, and humidifiers. In these home appliances, in order to save energy, it is important to produce steam on demand. As such, quick start-up and cut-off responses are required. However, most electrically steam generators require a relatively long time to produce steam due to the large heat capacities of water and of the heater. Zhao and Liao [1] introduced a newly process for rapid vaporization of subcooled water, in which a porous wick containing water is heated by a downward-facing grooved heating block in contact with the upper surface of the wick structure. They showed that saturated steam could be generated from room-temperature water within approximately 30 seconds at a heat flux of 41.2 kW/m^2. While Mori et al. [2][3] proposed a novel steam generator with a simple structure to quickly generate saturated and superheated steam. The structure of the generator is such that a fine coiled wire heater is installed inside a hollow space of the porous body, and the bottom of the porous block is soaked in a shallow water bath. The start-up response for production of the superheated steam is of the second order, and the maximum energy efficiency for input power is approximately 0.9. The reason for the instant evaporation in the use of water-containing porous body is that the heat capacity of liquid in meniscus is extremely small. Although the contact situation between the heater and the water-containing porous body has a great influence on the performance of the rapid superheated steam generator, it has not been clarified yet. Therefore, the effect has investigated experimentally changing the gap between fine wire heater and water-containing porous body in the present paper.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

2.1 Experimental apparatus

Figure 1 shows a schematic of the experimental apparatus. The porous block is 50 mm x 50 mm, and 80 mm in length. As a heater, a kanthal wire (ϕ 0.4 mm, L = 1,000 mm) was installed spirally inside a hole (ϕ 8 mm) made in the center of a 50 mm x 50 mm plane of a porous block. Extreme care was taken when connecting the kanthal wire with the copper wire, and crimped terminals were used in order to reduce the effect of contact electric resistance as much as possible. The bottom of the porous block was soaked in a shallow water bath, resulting in water being taken into the porous block through capillary action. The outside surface of the porous block was not treated and was thermally insulated. In order to consider the effect of the contact situation between the heater and the water-containing porous body on the performance of the rapid superheated steam generator, the outer diameter of the coiled heater was set to 8 mm and 7 mm, respectively, as shown in Fig.2. Therefore, the gap between the heater and the water-containing porous body is approximately 0.5 mm in the case of 7mm in outer diameter.

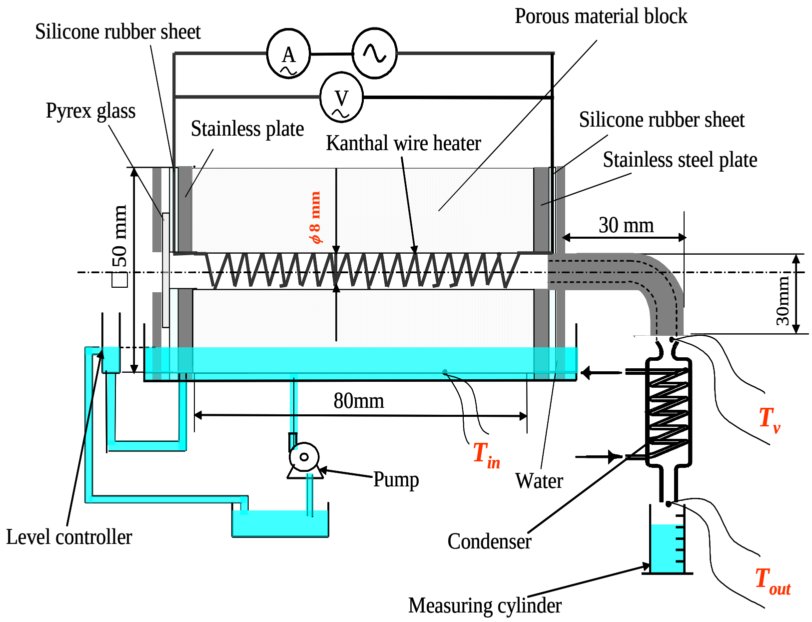

Fig.1 Schematic diagram of the experimental apparatus

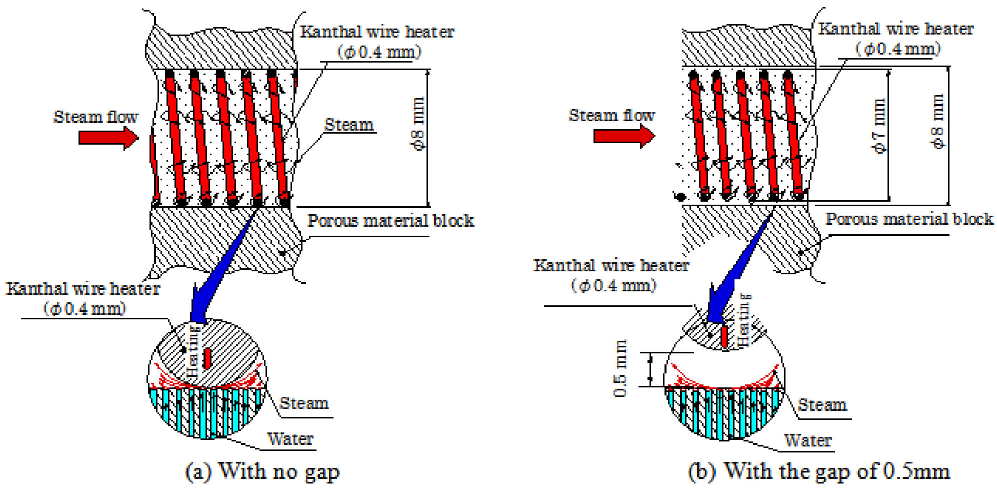

Fig.2 Schematic diagrams of gap between Kanthal wire heater and water–contained porous body.

2.2 Test porous material

The porous materials used in the present study, which are commercially available, were generally used as insulating firebricks. The porous material composed of fused SiO_2 (55 wt%) and Al_2O_3 (41 wt%).

Figure 3 indicates the pore size distribution of the test porous material as obtained by the mercury press-in method. The properties of mercury used in the measurement are a surface tension of 484.0 mN/m and a contact angle of 130.0 °. The average pore radius, mode radius, porosity, and effective thermal conductivity are 9 μm, 90.6 μm, 67.8%, and 0.33 W/(mK), respectively. In the present study, we present only the results for the porous material shown in Fig. 3 because the tendency of the results did not differ greatly.

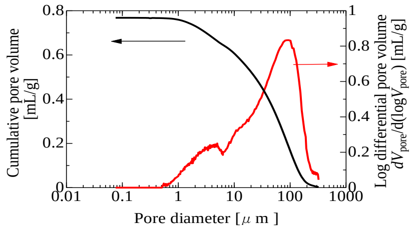

Fig.3 Pore diameter distribution of the test porous material.

2.3 Start-up and cut-off responses experiments

As stated above, in order to conserve energy, it is desirable to produce steam on demand. Namely, superheated steam must be produced from subcooled water at room temperature and stopped for a short time. The start-up and cut-off responses experiments have been performed as follows.

First, the temperature of the experimental apparatus was confirmed to be approximately room temperature just before the start-up response experiments. And then a kanthal wire heater was powered stepwise with an input power ranging from 100 W to 800 W. The cut-off response experiments were performed after the steady state was established, i.e., the steam temperature was saturated at steady state. A K-type thermocouple, T_{v1}, with a diameter of 0.1 mm (time constant: 0.2 s) was placed in order to measure the steam temperature at the outlet of an elbow tube (See Fig. 1). The reason for use of an elbow tube is to reduce error in steam temperature measurement due to the radiation from the wire heater with high temperature as much as possible.

2.4 Efficiency of energy utilization for input power

The energy utilization efficiency η for superheated steam generation is defined as follows:

$$\eta = \frac{Q}{P} \quad (1)$$

where Q and P are obtained as follows:

$$Q = \dot{m}c_{pl}(T_{sat} - T_{in}) + \dot{m}h_{hg} + \dot{m}c_{pv}(T_{v1} - T_{sat}) \quad (2)$$

$$P = I \cdot V \quad (3)$$

where $\dot{m}$ is the mass flow rate of steam, c_{pl} is the specific heat of water at constant pressure and(T_{sat}+T_{in}) $(T_{sat} + T_{in})/2$, T_{sat} is the saturation temperature, T_{in} is the temperature at the bottom of the porous block, h_{fg} is the latent heat of vaporization, c_{pv} is the specific heat of steam at constant pressure and(T_{sat}+T_v)/2, I is the electrical current, T_{out} is the temperature at the outlet of the condenser, and $V$is the voltage.

Three sheathed thermocouples having outer diameters of 1.0 mm were inserted into the bottom of the porous block, upstream and downstream of a condenser. The mass flow rate of steam was obtained by measuring the volume of condensed water for 20 min, confirming that T_{out} was lower than the saturation temperature during the measurement.

III. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Start-up and cut-off responses

Figure 4 shows the variation of T_{v1} with time for the case in which a kanthal wire heater was powered stepwise with an input power (200 W, 400 W, and 600 W) for the case with or without the gap between heater and porous body. For an input power of 600 W, it took only approximately 2 s to generate superheated steam at 300°Cfrom subcooled water at 25°C, and the final temperature of T_{v1} is approximately 700°C. In addition, as the input power increases, the time delay to produce steam decreases and final temperature increases. Thus, it is easy to increase the temperature and decrease the time needed for steam generation by increasing the input power. Moreover, cut-off responses are pretty good shown in the figure. The tendency of start-up and cut-off responses shown here is similar result we reported previously[3]. Irrespective of the gap, at 300 W or more, there is no difference in the start-up response because the water-containing porous surface is heated by radiation simultaneously with the start of heating. And the final temperature of the steam becomes higher in the case with a gap of 0.5 mm. This is because the heater temperature becomes extremely high since a heater is not in contact with the water containing porous body which resulted in reduction of the heat transfer coefficient. There was no change in cut-off response depending on the presence or absence of the gap.

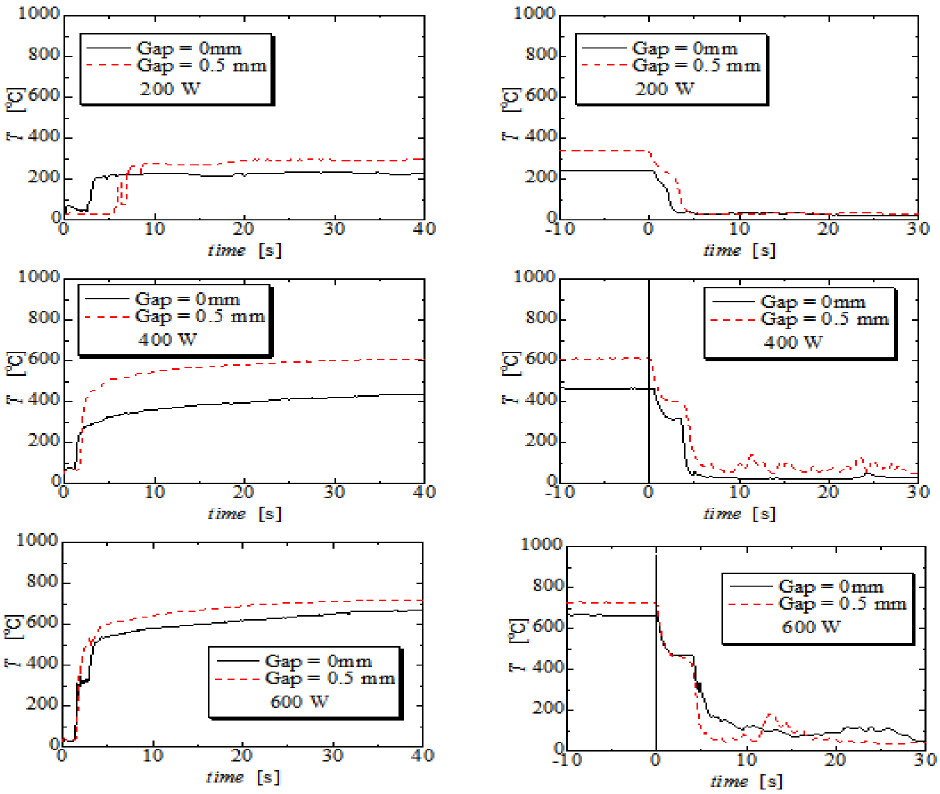

Fig. 4 Time change in T_{v1} during stepwise heating

3.2 Efficiency of energy utilization for input power

Figure 5 shows the energy utilization efficiency as defined by Eq. (1) together with T_{in}, i.e., the temperature at the bottom of the porous material (see Fig.1), as a function of input power. Interestingly, the energy utilization efficiency increases as the input power increases, whereas T_{in} decreases as the input power increases. For the highest energy utilization efficiency condition (P = 500 W), T_{in} is at room temperature .This inplies that the outer surface of the porous material is approximately adiabatic because the difference between room temperature and the surface temperature of the porous block is quite small. As such, the energy utilization efficiency is maximum at the highest input power. This interesting tendency was explained in the previous study [3]. Regarding to the effect of the gap on the energy utilization efficiency, it is not so large and the energy utilization efficiency is as high as 80% or more in any heating conditions.

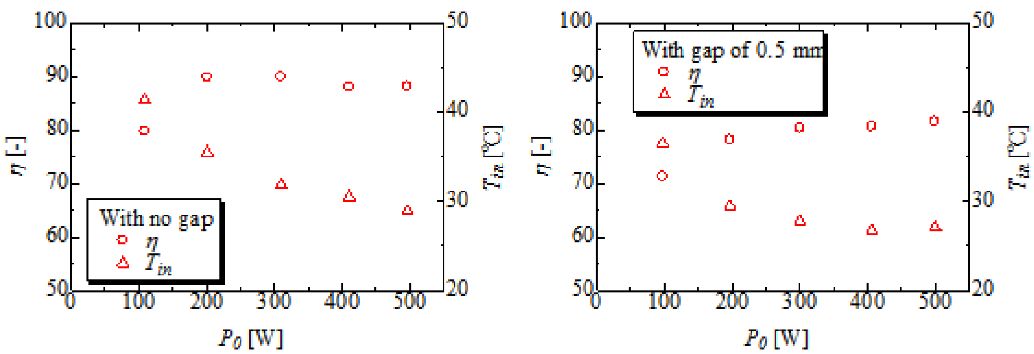

Fig.5 Energy utilization rate η and inlet temperature T_{out} as a function of input power *P*.

IV. CONCLUSION

We proposed a simple method for the rapid generation of superheated steam using a water-containing porous material. The start-up and cut-off responses are of the second order. Effect of the contact state between the heater and the water-containing porous body on the performance of the rapid superheated steam generator has been investigated experimentally. As a result, it is found that the response of superheated steam generation is less influenced by the gap between the heater and the water-containing porous body, and the larger the gap, the higher the steam temperature produced.

ACKNOWLEDGEMENTS

The present study was supported in part by research grand from the Japan Boiler Association.

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