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Development of ultra-high temperature SHS furnace using atmospheric-pressure microwave steam plasma

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HIGHLIGHTS

► We developed superheated steam furnace having ultra-high temperature over 1200 °C
► Microwave steam plasma was used as a heat source for a furnace.
► A discharge tube melted at low steam flow rate, high input power, and large diameter.
► Reducing diameter caused unstable formation of microwave steam plasma.
► Temperature distribution inside a furnace was strongly affected by steam flow rate.

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ABSTRACT

The development of superheated steam (SHS) furnace with ultra-high temperature was studied. We have proposed the use of atmospheric-pressure microwave-induced steam plasma as the heat source for SHS furnace. Since the sustainable operation and appropriate temperature distributions of microwave steam plasma play key roles in constructing an SHS furnace, the characteristics of steam plasma were initially investigated. The experimental results revealed that several conditions of microwave discharge existed for stable plasma formation. The limitations of heat-tolerance of a discharge tube, which are attributed to the rise of temperature, were confirmed at low steam flow rate, high input power, and large diameter of a discharge tube. Reducing the diameter of the discharge tube also caused the unstable formation of microwave steam plasma. Then, the furnace was assembled by joining the discharge tube of microwave steam plasma. The flat temperature distributions inside the furnace were observed as strongly affected by the steam flow rate. The proposed furnace could exhibit an ultra-high temperature over 1200 °C.

1. Introduction

Superheated steam (SHS) is hotter than the boiling point of water. Studies on SHS have been carried out for various physical and/or chemical processes such as drying technologies [1–5], sterilization of materials [6–8] and gasification of biomass and plastics [9–11]. The drying technique using SHS is an airless and oxygen-free treatment that administers high temperature steam as heating medium, evaporating moisture from the product at boiling point with no diffusional resistance [2]. The reduction of bacteria was successfully performed with the combination of SHS and vacuum treatments [6]. Many studies on heat and mass transfer mechanisms of SHS were conducted to develop processes that are more efficient by experimental and numerical methods [12–15]. Product qualities are strongly affected by treatment temperature of SHS, operation time, as well as conditions of materials [1,2,5,7].

An extensive temperature range and control of the temperature field is required to extend the SHS applications [16–19]. In the present practical SHS system, an induction heating (IH) method is being applied to achieve high temperature and temperature-controlled SHS [11,20]. However, a controllable maximum temperature (~1200 °C) is limited for IH method because metallic or electrically conductive materials are used in the heat exchange parts. Hence, the studies regarding ultra-high temperature SHS over 1200 °C has seldom been reported.

Microwave plasma is an electrical discharge with microwave as its energy source. It provides many advantageous features such as electrode-less discharge, high gas temperature (several thousand K), and a design that is compact and simple [21,22]. We have already succeeded in making pure steam plasma generated by microwave discharge under atmospheric pressure conditions and

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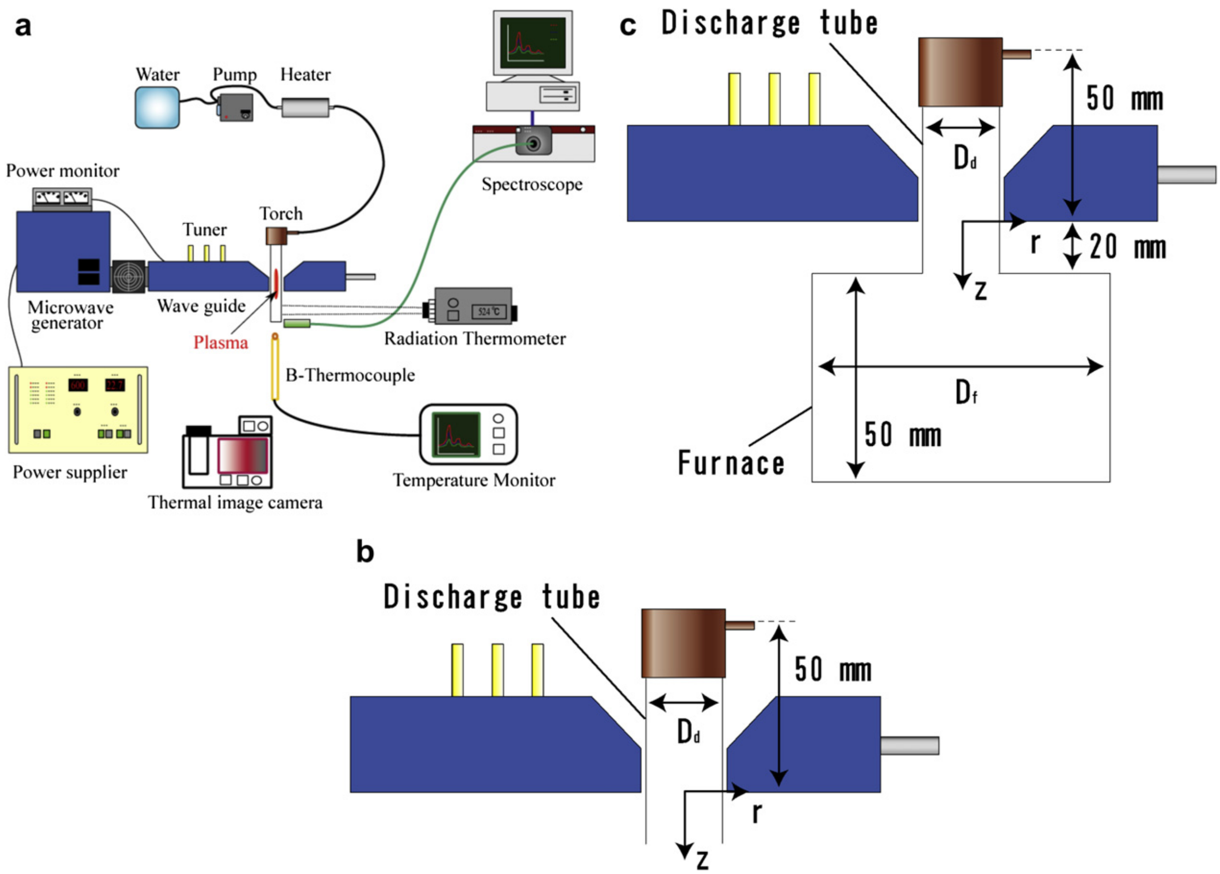

Fig. 1. (a) Schematic illustration of experimental setup, dimensions of (b) discharge tube and (c) SHS furnace.

applied to the various chemical reactions [23,24]. Our approach is to obtain ultra-high temperature SHS by using high-temperature microwave steam plasma as the heat source for SHS furnace. Having a controlled temperature distribution is required to enhance the effects of thermal treatments with SHS.

In the present study, we tried to develop an ultra-high temperature SHS furnace using atmospheric-pressure microwave steam plasma as a heat source. Stable and sustainable operations of microwave steam plasma are essential factors as these improve the practicality of an SHS furnace. First, the characteristics of microwave steam plasma were investigated from the perspective of stability. Second, we prepared two types of SHS furnaces with different dimensions and the temperature distributions of SHS were discussed.

2. Experimental

2.1. Characteristics of atmospheric pressure microwave steam plasma

Fig. 1(a) shows the experimental set-up. The experiment was conducted with 2.45-GHz microwave power supply having

Table 1
Experimental conditions for generation of atmospheric pressure microwave steam plasma.

Discharge tube diameter (inner (D_d) × outer) [mm]	8 × 10, 9 × 11, 9.5 × 11.5, 10 × 12, 10.5 × 13, 11 × 13, 12 × 14
Steam flow rate [mol/min]	0.43, 0.57, 0.72, 0.87
Input power [kW]	1.45, 1.60, 1.73

Table 2
Experimental conditions of ultra-high temperature SHS furnace.

Furnace	Quartz
Discharge tube diameter(inner (D_d) × outer) [mm]	11 × 13
Furnace inner diameter (D_f) [mm]	40, 60
Furnace height [mm]	50
Steam flow rate [mol/min]	0.57, 0.72, 0.87
Input power [kW]	1.45,1.60, 1.73

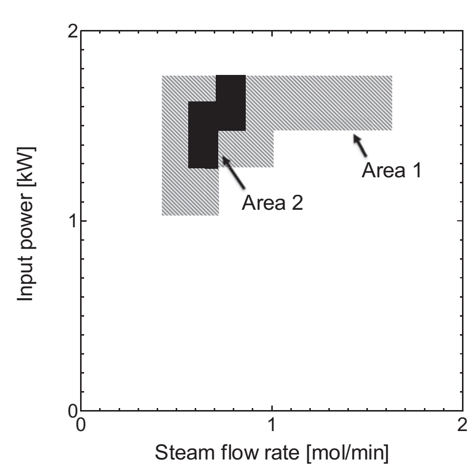

Fig. 2. Stable steam plasma formation conditions at an 11 × 13 discharge tube.