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On burnout performance of a rocket-engine-based incinerator devised for high burning rate of solid particles

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HIGHLIGHTS

- Rocker-engine-based-incinerator (RBI) is suggested as a new burning system of solid wastes.
- RBI is devised for high-performance burning and a compact chamber for mobility.
- Feasibility of the chamber of RBI designed with new concepts is tested for high burnout performance.
- Burning performance of RBI is higher than that of conventional incinerators by a factor of 10.

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ABSTRACT

A rocket-engine-based incinerator is proposed as a compact device of a solid-particle incinerator for high-performance burnout of wastes with solid phase. Burnout performance is investigated numerically in the chamber devised for this purpose. The present chamber employs design concepts of swirl flow and nozzle shape applied to a furnace of power-plants and a rocket combustor, respectively. As the first step, non-reactive flow field is analyzed in the incinerator with primary injectors and secondary injectors through which coal fuel and air are supplied. Deflection angle of a primary injector, incline angle of a secondary injector, gap between two-type injectors are selected as design parameters. Swirl number is adopted for evaluation of the degree of swirl flow and it is estimated over wide ranges of three parameters. Swirl number varies non-monotonically depending on the combination of the parameters. Burnout ratio increases with swirl number. High swirl number is attained over broad ranges of deflection and incline angles. From the numerical results, the design points with high burning performance can be found by maximizing swirl number. The proposed chamber has been verified to attain higher burnout performance than a conventional incinerator by a factor of 10.

1. Introduction

There are various wastes with solid phase gathered from homes, offices, and industrial factories. Conventional methods to dispose of solid-phase wastes in terminal are land-fill, dumping to the sea, and incineration. Land-fill requires broad space for storage of wastes and may cause the secondary environmental problems such as toil and groundwater contamination. Dumping wastes to the sea has the same environmental problems and is prohibited or will be in most of countries. Considering these limits to the two former methods, incineration or burnout would be the sole disposal of wastes although it still has the environmental problems of air pollution and ash disposal. Because these problems can be minimized through the appropriate pre-processes of solid wastes before burning and post-processes of combustion products from the incinerator after burning. Although they are to be solved by the technologies of the pre- and post-processes, incineration still has disadvantage of relatively greater expense than the others because it requires burning facilities such as supply system of wastes, incinerator or chamber, drain system, etc. Accordingly, a high-performance incinerator fits best with the economic constraint [1].

Efficient methods to reduce burnout cost and to increase performance have been proposed and adopted in conventional incinerators. For example, wastes are dried up to eliminate water content in them, atomized into small particles to enhance combustion efficiency, and vortex generated in an incinerator is to enhance mixing with air [2]. Aerodynamic control made by primary and secondary injectors as well as jets from rectangular slot-burner can enhance fuel–air mixing in a non-reactive flow [3,4]. With these methods applied, conventional solid-waste incinerators with high-class performance have a range of burning performance, 5–15 kg/hr m^3 [5–7]. Solid wastes consist of components of

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Nomenclature

A	pre-exponential factor
B_r	burnout ratio
$D_{i,m}$	mass diffusion coefficient for *i*th species
$D_{T,i}$	thermal diffusion coefficient for *i*th species
E	energy
E_a	activation energy
$\vec{F}$	external force
G_y	axial momentum
G_θ	angular momentum
$\vec{g}$	gravitational body force
h	enthalpy
$\vec{j}_j$	diffusion flux of *j*th species
k_{eff}	effective conductivity
L	length
l_{ch}	characteristic length of the chamber
M_w	molecular weight
m	mass
p	pressure
R	radius of the chamber
r	radial coordinate
R_i	net reaction of production of *i*th species
R_m	universal gas constant
Sc_t	turbulent Schmidt number
S_h	heat of chemical reaction
S_w	swirl number
T	temperature
t	time
u_y	axial component of velocity
u_θ	tangential component of velocity
$\vec{v}$	velocity vector
Y_i	mass fraction of *i*th species
Δ	gap between the primary and the secondary injectors
μ_t	turbulent viscosity
ρ	density
θ_d	deflection angle of the primary injector
θ_i	incline angle of the secondary injector
$\bar{\bar{\tau}}$	stress tensor
$\vec{\tau}_{eff}$	effective stress

hydrocarbon and thus, they can be regarded as solid fuels or coal with equivalent rank. Accordingly, performance of boilers or furnaces generating power through burning of coal can be compared with that of an incinerator. Industrial boilers for coal burning in power-plants have a typical range of 8–27 kg/hr m^3 [8,9]. These incinerators have high burning performance of several hundreds of tons per day and are built as a part of stationary large facilities on a building site [10,11], where wastes are burned in a large scale. For burning of wastes in a conventional incinerator, wastes are collected from each source of wastes, transported to the site of burning facilities, and accumulated for a long time. In the other aspect of wastes incineration, it would be more cost-effective and convenient to burnout wastes at once when they come from each source, i.e., to do *in situ* burnout. Especially, when animal carcass is burned out for instant disposal, a mobile incinerator would be helpful to prevent the environment from a secondary infection caused by diseased carcass. But, conventional incinerators are not suitable for disposal of small amount of wastes immediately whenever they come in a small scale. For mobility to each source, a chamber with small volume is required.

In this regard, a compact incinerator with high burning rate is devised in this study for the purpose of *in situ* burnout. Lots of sub-components in burning facilities need to be improved for enhancement of burning performance. Of them, the key component is the incinerator or chamber, where burning of wastes occurs, and it is focused on in this study. A compact incinerator with a new concept is designed with the target of higher burnout performance than that of a conventional one by a factor of 10 and its feasibility for high performance is investigated numerically.

2. Conceptual design of a high-performance incinerator

The incinerator to be devised should meet two requirements of a compact size for mobility intended to do *in situ* burnout and high burnout performance which surpasses that of a conventional incinerator by a factor of 10, for example, 270 kg/hr m^3. To meet them, the incinerator should be characterized by a combustion chamber with high energy density, which means high fuel flow rate into the chamber with small volume. High combustion efficiency should be guaranteed to burnout almost fuel supplied. It cannot be attained simply by scaling down existent conventional incinerators, but by adopting new design concepts for highly enhanced incineration.

High burnout performance is followed by high flame temperature, strong turbulence for enhanced fuel/air mixing, and long residence time of fuel in a chamber. Especially, swirl flow and recirculating flow are critical in both aspects of temperature and residence time in a chamber [12–14]. With regard to non-reactive flow in an incinerator, there can be found lots of studies on flow pattern suitable for burnout [15], flow speed, mixing, distributed burning [16], measurement in turbulent flow fields, and effects of swirl flow on recirculation zone [17,18]. Review of these previous works leads to swirl flow of significance in a chamber for high-performance burning. It is also a critical flow character adopted in tangentially-fired furnace, and two recent numerical works [19,20] reported that species concentrations and char burnout rates would depend on load level in the furnace, where tangential fire-ball is formed. Accordingly, generation of swirl flow is still kept and emphasized in the present incinerator. An essential concept to be considered furthermore is to burnout solid particles with high energy density. To realize it, the present chamber follows the shape of a rocket engine combustor adopted in aerospace propulsion because the combustor has the largest energy density of commercial chambers used at present. That is, the incinerator to be devised adopts the combined technologies from both conventional incinerators and rocket engines. Here, it is called a rocket-engine-based incinerator (RBI), of which basic geometry is shown in Fig. 1. The RBI consists of two chambers; one is the first chamber at the top and the other is the second one at the bottom. It follows a nozzle shape from the converging part of the first chamber to the exit of the second chamber. Two chambers are connected with each other by a narrow channel or throat. Depending on the design of the channel and the second chamber, a secondary burning of unburned fuel from the first chamber can be induced, leading to extra burnout of fuel in the second chamber. Solid fuel or wastes and air are supplied through injectors mounted around the first chamber. The