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Research Paper

Numerical investigation of the heat transfer performance of water-cooled incineration grates with various channel designs

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HIGHLIGHTS

- Cooling of incineration grates is investigated numerically.
- Three different designs of cooling channels are considered.
- 3D CFD has been used to evaluate heat transfer performance.
- Various mass flow rates and heat fluxes are considered.
- The baffle channel is the best choice among three different designs.

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ABSTRACT

This study investigates the effect of the geometry of the cooling channel on the cooling performance of a unit grate using a three-dimensional computational fluid dynamics approach. Three different geometries of the cooling channel, i.e., serpentine, wavy, and baffle channels are considered. To evaluate the cooling performance, evaluation indicators, including the maximum temperature, average temperature, temperature uniformity, and pressure drop are compared. In addition, figure of merit, i.e., heat transfer per unit pumping power, is also compared for three channel designs. According to these indicators, it is concluded the baffle channel is the best choice.

1. Introduction

Waste incineration is a well-established method for converting waste into energy. It facilitates the management of a wide range of industrial and domestic wastes [1–4]. By incinerating waste and hazardous materials, we can reduce their volume whilst capturing or destroying any potentially harmful substances released during incineration [3]. We can also recover energy and materials such as phosphorus, ferrous and non-ferrous metals, and rare earth elements from incinerated wastes [5,6]. The waste incineration process usually comprises pretreatment, thermal treatment, and post-treatment [2,4]. The pretreatment stage includes the reception, storage, pretreatment, and loading of waste and raw materials. The combustion and energy recovery/conversion occur during the thermal treatment stage. The post-treatment stage includes steps such as flue-gas cleaning, emissions monitoring and control, waste water treatment, and solid residue discharge/disposal. The key step in the waste incineration process is the thermal treatment stage. Several types of thermal treatments have been developed, including grate incinerators, rotary kilns, fluidized beds, and pyrolysis and gasification systems [1–3]. Although approaches vary significantly depending on the type of thermal treatment, its aim is to oxidize the combustible materials contained in the waste [2]. Among the various thermal treatment methods, grate incinerators are highly energy efficient and have been used to treat a wide range of waste, including commercial and industrial non-hazardous waste, sewage sludge, and clinical waste [7,8].

In grate incinerators, waste is transported to the incineration grates through a waste feeder, as shown in Fig. 1, and combustion occurs on the surfaces of incineration grates. Hence, the waste is supported by the incineration grates, and the heat flux at the surface of the grates is high. It is essential to equip the incineration grates with cooling systems to protect them from thermal damage. Air cooling systems are often used because the air both cools the incineration grates and supplies the oxygen required for combustion

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Nomenclature

u_i	velocity components in the x, y, z direction (m s^{-1})
$\overline{u}_i$	mean velocity component in the x, y, z direction (m s^{-1})
u'_i	fluctuation values of velocity components in the x, y, z direction (m s^{-1})
T	temperature (K)
$\overline{T}$	mean temperature (K)
T'	fluctuation values of the temperature (k)
T_{inlet}	inlet temperature (K)
p	pressure (Pa)
$\overline{p}$	mean pressure (Pa)
P_{outlet}	outlet pressure (Pa)
k_s	thermal conductivity of the solid material (W m^{-1} K^{-1})
k_f	thermal conductivity of the cooling fluid (W m^{-1} K^{-1})
C_{pf}	specific heat of the cooling fluid (J kg^{-1} K^{-1})
s_i	source term of momentum equations in the x, y, z direction
s_e	source term of the energy equation
$\dot{m}_{inlet}$	inlet mass flow rate (kg s^{-1})
Q_{flux}	heat flux (W m^{-2})
T_{avg}	average temperature (K)
FoM	figure of merit (m^3 kg^{-1})
ρ	fluid density of the cooling fluid (kg m^{-3})
μ	dynamic viscosity (Pa s)
μ_t	turbulent viscosity
σ_T	standard deviation of the temperature (K)
κ	turbulent kinetic energy
ε	dissipation rate of the turbulent energy

[2,9]. Recently, researchers have considered equipping incineration grates with water cooling systems instead of air cooling systems [10,11]. Water cooling has several advantages over air cooling: the heat transfer efficiency is higher, there is no excess oxygen, and waste heat can be recovered. To obtain efficient heat transfer performance, the optimum design of the cooling water pathway is essential; however, little research has been conducted to this end.

In this study, we numerically investigate the heat transfer performance of a variety of cooling channel designs: a serpentine pipe, a wavy channel, and a channel with baffles. In the real gate incinerators, the grates are connected to form a single stage and the stack of stages forms incineration grates (Fig. 1). In order to simplify analysis, we consider a unit grate in which cooling channels are placed. The serpentine pipe is the most common type of cooling channel for a variety of applications. The wavy channel is usually used to enhance complex flow patterns, and the baffle channel is designed to minimize the pressure drop. We determine the effects of the shape of the cooling channel on the heat transfer performance of the incineration grate by evaluating the maximum temperature, average temperature, temperature uniformity, and pressure drop under a variety of operating conditions. Operating conditions are varied by changing the mass flow rate of the cooling water and the heat flux applied to the heating area. We also determine the figure of merit (FoM) of each cooling channel geometry under each operating condition.

2. Mathematical model

Our physical model of the unit grate contained a solid region and a fluid region; this allowed conjugate heat transfer between the solid grate and the cooling water. The heat generated by the waste combustion is represented by a constant heat flux applying to the heating area as shown in Fig. 1. We model three types of cooling channels: the serpentine pipe, wavy rectangular channel, and rectangular baffle channel. These are shown in Fig. 2 and the geometric parameters of the channels are detailed in Table 1. The exact geometric parameters of the baffle channel was obtained from manufacturer (GEQ solution co., Ltd) and the geometric parameters of the serpentine pipe and the wavy channel were estimated from the shape information in manufacturer's technical brochures [12,13].

2.1. Governing equation

As conduction is the main heat transfer mode through the solid region, the governing equation in this region is

$$\frac{\partial}{\partial x_i}\left[k_s \frac{\partial T}{\partial x_i}\right] = 0, \quad (1)$$

where k_s is the thermal conductivity of the solid material, and T is the temperature.

We consider both fluid flow and convective heat transfer in the fluid region and the fluid is assumed to be incompressible. Turbulent flow is taken into account using the Reynolds-averaged Navier-Stokes equations [14,15].

The continuity equation is as follows:

$$\frac{\partial(\rho \overline{u}_i)}{\partial x_i} = 0, \quad (2)$$

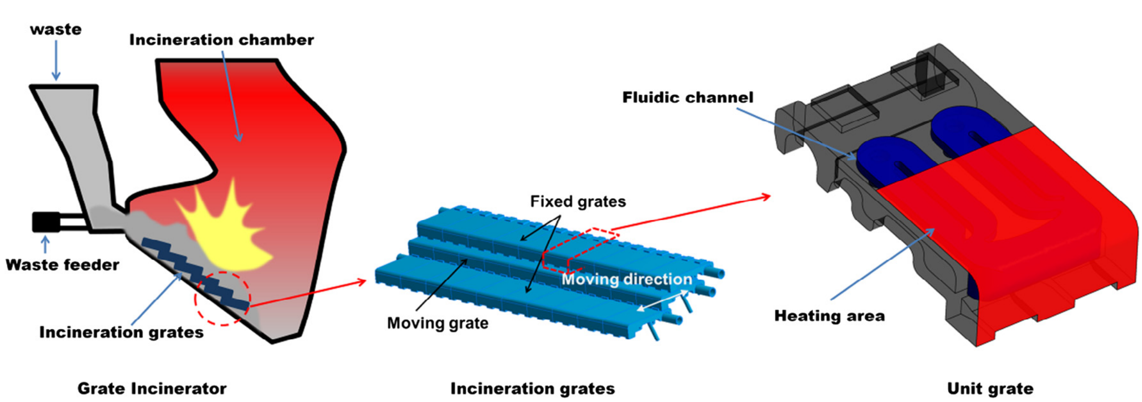

Fig. 1. Schematic diagram of the grate incinerator, incineration grates, and a unit grate.