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GAS-SOLID HEAT TRANSFER IN WASTE HEAT RECOVERY DEVICE WITH DIFFERENT PIPELINE ARRANGEMENTS

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ABSTRACT

In this paper, gas-solid heat transfer in waste heat recovery device with different pipeline arrangements is studied. The pipeline can enhance heat transfer in waste heat recovery device, and the system with pipeline has higher outlet gas temperature. Compared with paralleled arrangement, temperature distribution of staggered arrangement is more uniform and heat transfer is better. It addition, the decrease of inlet velocity and particle diameter can improve the outlet gas temperature.

Keywords: waste heat recovery device, porous media, local thermal non-equilibrium, gas solid heat transfer.

NONMENCLATURE

u	velocity (m/s)
T	temperature(K)
h	heat transfer coefficient ($Wm^{-1}K^{-1}$)
d	particle diameter (m)
c	specific heat ($Jkg^{-1}K^{-1}$)
Nu	Nusselt number (-)
Symbols	
ε	porosity (-)
λ	thermal conductivity ($Wm^{-2}K^{-1}$)
μ	dynamic viscosity (m^2/s)
ρ	density (kg/m^3)

1. INTRODUCTION

The steel industry has always been the top priority of the national industry, and the energy consumption of blast furnace steelmaking can reach 40% of total energy consumption in the steel industry, 10%~15% of total energy consumption in the country, belonging to the high energy-consuming industry [1].

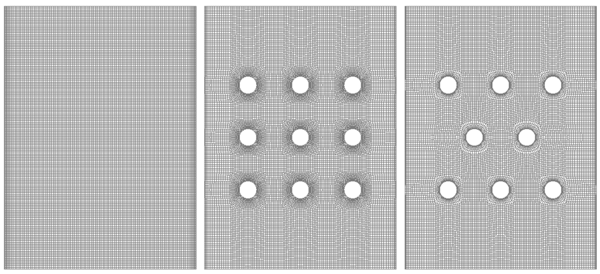
For these high-grade waste heat, many scholars have proposed different heat recovery methods, such as packed bed waste heat recovery [2-5], gravity bed waste heat recovery [6-8], fluidized bed heat back program waste heat recovery [9]. However, there is still a lack of research on gas-solid heat transfer with different pipeline arrangements.

In this paper, gas-solid heat transfer in waste heat recovery device with different pipeline arrangements is simulated and analyzed. In addition, the effects of pipeline arrangement, intake velocity and particle diameter are further considered.

2. PHYSICAL MODEL AND VALIDATION

2.1 Physical model

The schematic diagram of waste heat recovery device is shown in Fig 1, and different pipeline arrangements are studied. High temperature granular and cold gas exist countercurrent flow heat transfer, and the cooled particles and high temperature gas are obtained for subsequent processes.



(a) Without (b) Paralleled (c) Staggered pipeline
Fig 1 Waste heat recovery device

The gas-solid heat transfer is complex, so the following assumptions are made:

(1). The simulation process is steady state, and the operating parameters are constant;

(2). Porous media model is used for simulation, Porous media is a homogenous material, and the temperature of the particles is uniform.

(3). Considering convection and heat conduction between the solid and the fluid in the porous media, regardless of influence of radiation and heat loss;

2.2 Governing equation

Gas continuous equation:

$$\frac{\partial \rho u_i}{\partial x_i}=0 \tag{1}$$

Gas momentum equation:

$$\frac{\partial}{\partial x_i}\left(\rho u_i u_k\right)=\frac{\partial}{\partial x_i}\left(\mu\frac{\partial u_k}{\partial x_i}\right)-\frac{\partial p}{\partial x_i}+\rho g+S_i \tag{2}$$

When porous media model is used, source term is added to momentum equation as:

$$S_i=-\left(\frac{\mu}{\alpha}u_i+\frac{1}{2}C_2\rho_g\,|u|\,u_i\right) \tag{3}$$

where the viscous resistance coefficient and the inertia resistance coefficient can be expressed as [10]:

$$\frac{1}{\alpha}=\frac{150(1-\varepsilon)^2}{\varepsilon^3 d_{\mathrm{p}}^2} \tag{4}$$

$$C_2=\frac{3.5(1-\varepsilon)}{\varepsilon^3 d_{\mathrm{p}}} \tag{5}$$

The local thermal non-equilibrium energy equations are:

$$\frac{\partial}{\partial x_i}\left(\rho_s c_{p,s}u_i T_s\right)=\frac{\partial}{\partial x_i}\left(\left(1-\varepsilon\right)\lambda_s\frac{\partial T}{\partial x_i}\right)-h_e\alpha\left(T_s-T_g\right) \tag{6}$$

$$\frac{\partial}{\partial x_i}\left(\rho_g c_{p,g}u_i T_s\right)=\frac{\partial}{\partial x_i}\left(\varepsilon\lambda_g\frac{\partial T}{\partial x_i}\right)+h_e\alpha\left(T_s-T_g\right) \tag{7}$$

The Nu is used association proposed by Wakao [11]:

$$Nu=\frac{hd_p}{k_g}=2.0+0.6\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3} \tag{8}$$

The internal heat transfer of particles on the overall heat transfer coefficient is considered. The effective heat transfer coefficient according to Jeffreson [12] can be expressed as:

$$\frac{1}{h_e}=\frac{1}{h}\left(1+\frac{Bi}{5}\right)\beta^2 \tag{9}$$

Where the thermal capacity ratio *β* and the heat capacity ration V_H can be expressed as:

$$V_H=\frac{\rho_s c_s\left(1-\varepsilon\right)}{\rho_g c_g \varepsilon} \tag{10}$$

$$\beta=\frac{V_H}{V_H+1} \tag{11}$$

According to Achenbach [13], the specific surface area can be expressed as:

$$\alpha=\frac{6\left(1-\varepsilon\right)}{d_p} \tag{12}$$

The equations are solved by Fluent. The local thermal non-equilibrium energy equations are corrected by UDF and UDS. The material density, specific heat and other parameters are set by UDF. The grid is divided by ICEM, and the pressure velocity coupling is solved by SIMPLE. The turbulence model adopts k-ε model, and residual convergence criterion is less than 10^{-6}.

The air density is 1.225 kg/m^3, and particle density is 2900 kg/m^3. Specific heat of gas and particle can be calculated as follows:

$$\begin{aligned}c_{p,g}&=1908.911+7.054\times10^{-1}T_{\mathrm{g}}+1.67\times10^{-3}T_{\mathrm{g}}^2\\&-1.225\times10^{-6}T_g^3+3.080\times10^{-10}T_g^4\end{aligned} \tag{13}$$

$$c_{p,s}=1014+6.21\times10^{-2}T_g-0.347\times10^{8}T_g^{-2} \tag{14}$$

2.3 Model Validation

Experimental results of steady heat recovery from Feng et al [14] are used to verify present model. The experimental and simulation results are compared as Table 1, and they have good agreement.

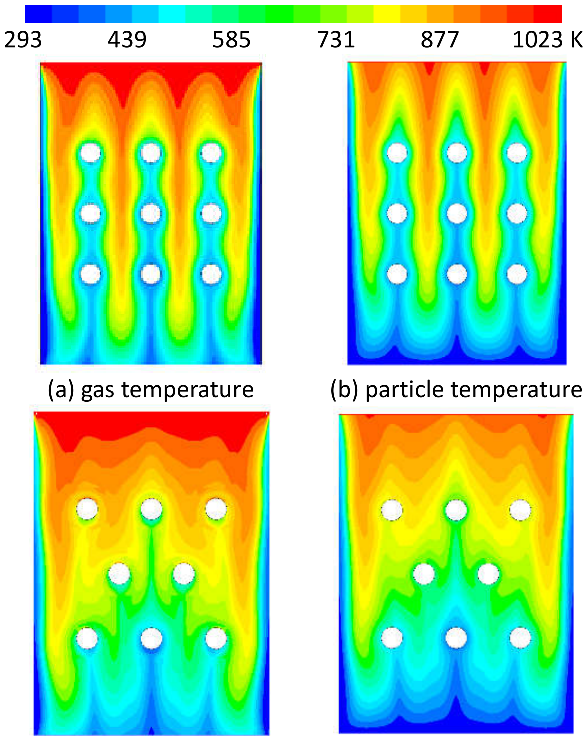
3. RESULTS AND DISCUSSION

3.1 Basic heat transfer performance

Fig 2 presents temperature distributions in different heat recovery devices. When there are pipelines, the flow changes, and then gas-solid heat transfer will be significantly enhanced.

Table 1 Simulation and experimental comparison

Experimental condition	Particle outlet temperature (K)			Air outlet temperature (K)		
	Measurement	Calculation	Relative error	Measurement	Calculation	Relative error
condition 1	394	412	3.74%	795	784	-2.24%
condition 2	379	398	3.62%	748	735	-2.94%
condition 3	383	396	2.56%	756	744	-2.66%



(a) gas temperature (b) particle temperature

(c) gas temperature (d) particle temperature

Fig 2 Temperature in different systems

Compared with paralleled pipeline arrangement, the staggered arrangement can reduce the temperature heterogeneity in the heat transfer process, and heat transfer is expected to be enhanced better.

3.2 Effect of inlet gas velocity

Fig 3 shows outlet gas and particle temperatures with different inlet gas velocity in different internal components. The outlet gas temperature in staggered pipeline system is higher than that in paralleled one, and that without pipeline is lowest. As a result, heat transfer with staggered pipeline is better, because its temperature distribution is more uniform as Fig. 2.

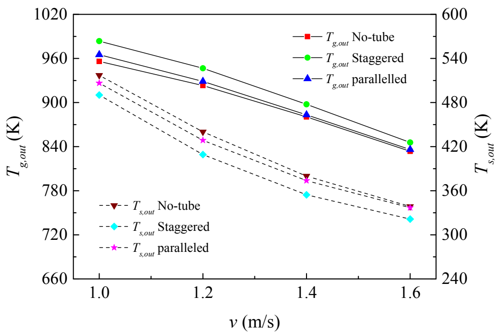


Fig. 3 Outlet gas and particle temperatures with different inlet gas velocity

In addition, outlet gas temperature drops with inlet gas velocity increasing. As inlet gas velocity increases, heat transfer between gas and particle increases, which leads to a decrease in outlet particle temperature. At the same time, mass flow rate of gas becomes larger, and outlet gas temperature decreases.

3.3 Effect of inlet gas temperature

Fig 4 shows outlet gas and particle temperatures with different inlet gas temperatures. In general, outlet gas and particle temperatures have similar tendencies with different inlet gas temperatures and compounds. As inlet gas temperature is increased, inlet enthalpy of gas increases, and outlet temperatures of gas and particle almost linearly rise, and outlet particle temperature changes more quickly.

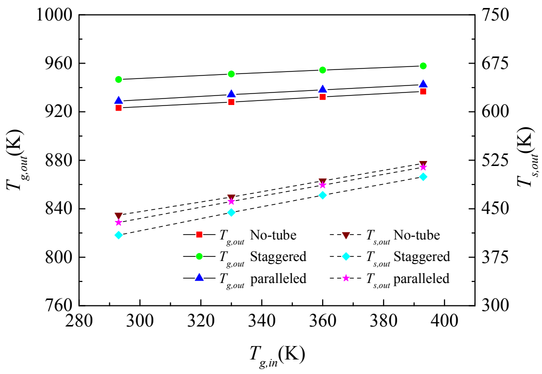


Fig 4 Outlet gas and particle temperatures with different inlet gas temperatures

3.4 Effect of particle diameter

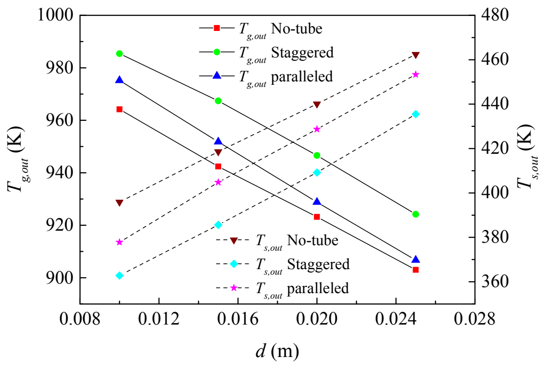


Fig. 5 Outlet gas and particle temperatures with different particle diameters

Fig. 5 shows outlet gas and particle temperatures with different particle diameters. As the particle diameter is reduced, gas-solid heat transfer area and effective heat transfer coefficient increase significantly, so outlet gas temperature increases and outlet particle temperature decreases. The outlet temperatures of gas and particle in the system with/without pipeline have similar tendency, and that with staggered arrangement has best performance.

3.5 Effect of pipe wall condition

Fig. 6 shows outlet gas and particle temperatures with different pipe temperature. As the pipe wall temperature increases, outlet temperatures of gas and the particles increases.

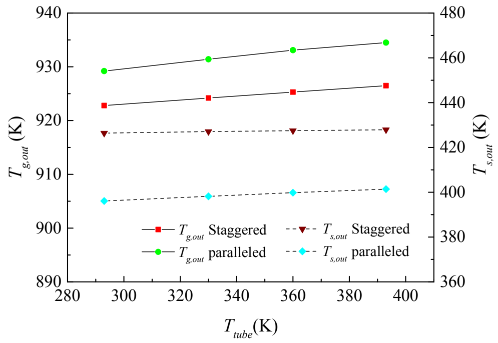


Fig. 6 Outlet gas and particle temperatures with different pipe temperature

4. CONCLUSIONS

The gas-solid heat transfer in waste heat recovery device with different pipeline arrangements is studied, and conclusions are as follows.

(1) When there are pipelines, gas-solid heat transfer can be significantly enhanced. Compared with paralleled arrangement, the system with staggered arrangement has more uniform temperature distribution and higher outlet gas temperature.

(2) As inlet gas temperature/pipe wall temperature increase or gas velocity decreases, outlet temperatures of gas and particle both increase. As particle diameter is reduced, effective heat transfer coefficient increases, so outlet gas temperature increases and outlet particle temperature decreases.

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