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Experiment on fine particle purification by flue gas condensation for industrial boilers

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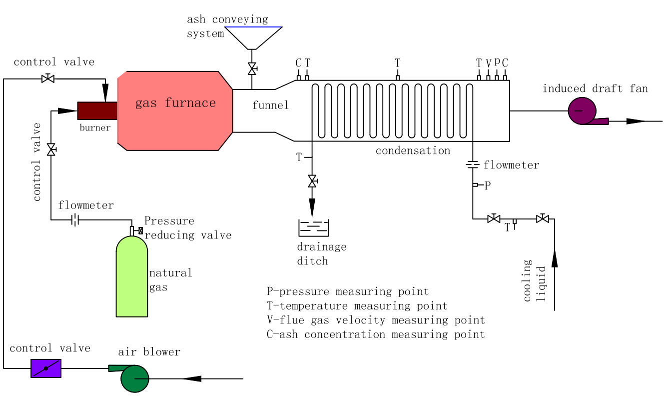
GRAPHICAL ABSTRACT



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ABSTRACT

The paper reports the numerical investigation and experimental investigation of flue gas condensation and fine particle removal of an integrated technology (condenser, the same below) for industrial boiler. The average temperature drops to 159 °C and velocity increases to 22 m/s at the outlet of condenser. Furthermore, it is estimated that the mean flue gas condensation efficiency of the condenser reaches to 99.02% and its particle removal efficiency arrives at 94.8% on average under the identical operational conditions. As for the classification of dust removal, the volume fraction of flue ash denoted $PM_{2.5}$ and PM_{10} decreases by 57.64% and 43% respectively. Finally, correlation between flue gas condensation and fine particle removal are positive. Therefore, the condenser can be applied to release the latent heat and reduce the emissions of fine particles. This paper can provide reference with the design, function and test of the heterogeneous condensation technology.

1. Introduction

The heavy emission of particle pollutants, especially for aerodynamic diameter ≤2.5 μm ($PM_{2.5}$) or 10 μm (PM_{10}), has a huge impact on the global environment and human health [1]. The impurities particle (PM) can be traced back to the feedstock composition, which contains many heavy metals [2]. Due to incomplete combustion of fossil fuels, some leakage during transport and imperfect desulfurization or denitrification, the particle diameter of the PM emitted has become increasingly serious. Generally, industrial boilers and furnaces are major accountable for relieving more than 35% percent of the undesirable fine particles in recent years [3]. Other

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causes are private vehicles, power plant boilers and many other chemical factories used in the city and countryside.

Since fine particles are more likely to penetrate through traditional purification systems [4], some flue gas technology, like heterogeneous condensation can be applied to the purification of fine particles [5], and the operating parameters like temperature, velocity have to be adjusted perfectly [6]. The Navier-Stokes equations and Eulerian two-fluid formulation are employed in many multiphase flow systems to obtain the temperature [7] and velocity fields [8].

The heterogeneous condensation is targeting on create a coarse liquid-particle interactions, in which the particle enlarged probability can be increased to the limit of Greenfield Gap [6]. The precondition of heterogeneous condensation of water vapor and film is supersaturation environment and cold wall [9]. When the water vapor temperature is lower than the corresponding critical supersaturation water temperature, the enlarged particle can be easily absorbed by droplets and increase the particle deposition efficiency, or removed by the demister [10]. The flue gas condensation ability and heterogeneous nucleation probability is simultaneously increased when adding steam [11]. Different purification system inlet temperature, like ranging from 60 °C to 120 °C, may affect the droplet condensation ability, but may not affect total particle removal efficiency [12]. The temperature of desulfurization solution is another important factor for simultaneously removal SOx and dust, the improvement of the total dust removal efficiency decrease from 34.96% to 22.52% when the inlet liquid temperature changing from 37 °C to 63 °C. when using heterogeneous condensation technology in a classic wet desulfurization or dedust system, the temperature of flue gas can be easily goes towards the saturated state (50 °C–60 °C) [13]. But the vapor saturation is hard precondition for flue gas of industrial boiler, and increasing the relative humidity seems to be an effective way to achieve it [14]. Several certain types of integrated technology of heat control and pollutant removal were tested. It is suggested temperature management has a positive correlation with pollutant purification, so they are applied to the biomass gasifier [15] and diesel vehicles [16]. Meanwhile, it is stated the feasibility of reducing the particle emission rate and improving the droplet control effect, raising the heat transfer efficiency by decreasing the outlet temperature [17].

Generally, the mean velocity values of flue gas given are between 3 m/s and 35 m/s [18]. The supersaturation environment gained and fine particles removal when the velocity of flue gas is relatively low for scrubber [19]. Also, there is positive correlation between velocity of desulfurized flue gas and particle removal efficiency [13]. By applying to the flue gas desulfurization, not only the condensable vapor could reach to 20 g/m^3, but also the particle removal efficiency could be improved by 30–40% through heterogeneous condensation technology [20]. When using demister or other fine particle removal devices, the fine particle removal efficiency can be significantly increased by heterogeneous condensation [21]. When there is a raise in gas saturation, the generated acid mist is decreased, but sometimes it produces much more smog [22].

There is correlation between particle diameter size and gas phase pollutant concentration [23]. And particle size distribution could be markedly shifted by particle agglomeration, thus the particle concentration could be significantly decreased [24]. Generally, the dominant forces are changing in different liquid-particle interactions [6]. There has negative correlation between particle rebound effect and surface adhesion force when St > 1.0 [25]. Thermophoresis force is the reason why most of the fine particles have high-speed deposition rate [26]. Also, high number fraction force is the major reason, which causes the increasing system outlet concentration of fine particles. While the system disequilibrium effect caused by heat transfer, the vapor thickness is of great importance on the system stability [27]. Vast majority of the PM adheres to the surface when there is a high volume fraction because of adhesion force [28]. By reducing the dead zone, and promoting the velocity along the light attenuation direction, there is an increase in dust particles collection [29].

Moreover, owing to commercial industrial boiler are smaller in its size and evaporation capacity, the average cost like application, transporting and other are far from reasonable, by which comparing to high capacity official boiler [30]. Since the aerosol purification technologies are auxiliary used, the commercialization of operating and developing of are much difficult [31].

Framed in this background, it is necessary to build a cross-flow condenser for industrial flue gas purification. Water is one of the most economic and effective medium. Also, water-based condenser can be applied to present particle removal process. The main purpose of this research is to design, build and validate a novel model for wet dedust system using water as agent in a condenser. The novel developed system employs the liquid-particle interaction and particle forces comparison theory. The influences of flue gas temperature, velocity on the whole system performances are investigated. The effects of inlet condensate, dust concentration on flue gas condensation and dust removal efficiency are studied. The change of particle size distribution and particle volume fraction are then analyzed.

2. Numerical experiment

2.1. Model assumptions

In this paper, to achieve accurate governing equations, based on former studies the following assumptions are made:

(1) The system is isothermal.
(2) Flows are laminar in both phases.
(3) Inlet and outlet segments of shell side are longer than it's original.
(4) Fluid inside condensers is incompressible and Newtonian
(5) The influence of the gap on flow field between the baffle plate and the heat transfer tubes is not considered and the particle diameter remains constant.
(1) The rate of heat transfer, which occurs between gas and liquid film on the surface of tube is assumed unchangeable, and the temperature of the tube is constant.

2.2. Model performance assessment

In this study, the computational domain consists of two shell-and-tube type condensers (ST type) and two plate-type (P-type) condensers, composed of four or six circular or rectangle tubes or plates, respectively. Depending on the condensers configuration, the geometrical model should include a row of several tubes and several division plates connected to the wall. All internal heating tubes and the neighboring regions of the shell and the wall are under similar condition. For all condensers, the mixed air and particle act as the gas phase while the water acts as the liquid phase.

The main operating parameters of condensers, such as wall function selection and system inlet, are summarized in Table 1 and model structures of the condenser are given in Table 2. Regarding shell-and-tube type condenser, there are 21 holes and the column diameter is 0.032 m, the fractional free area is 0.23, plate spacing is 0.046 m, plates are 0.002 m thick, and shell/tube/baffle diameter is 0.025 m. Regarding the plate-type, the diameter of each pipe is 0.05 m, the angle between the plate and the axis is 30° and the attach angle between two plates is 150°.

The no-slip boundary describes the solid wall and a free slip condition is given for gas surface. As regards the gas, thermal conductivity is k = 85 W/(m·°C), specific heat is c_p = 1320 J/(kg·°C) and