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# The effects of wall friction and solid acceleration on the mal-distribution of gas–solid flow in double identical parallel cyclones

Xin Mo, Runxia Cai, Xiaodan Huang, Man Zhang, Hairui Yang *

*Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Beijing Key Laboratory of $CO_2$ Utilization and Reduction Technology, Department of Thermal Engineering, Tsinghua University, Beijing 100084, China*

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ABSTRACT

The uneven gas–solid flow in parallel cyclones, which is called as the mal-distribution in publications, has been widely confirmed. Although there is non-uniform gas–solid flow in the riser, the parallel cyclones would influence the distribution of gas–solid flow due to the pressure drop constraint. Based on the pressure drop constraint and an empirical correlation for cyclone pressure drop, this paper analytically investigates the mal-distribution of gas–solid flow in double identical parallel cyclones, and measures to limit the mal-distribution are suggested. Due to the effects of wall friction and solid acceleration, the change of pressure drop with the increase of solid loading shows a nonlinear characteristic. The inflection point (at where the cyclone has the minimum pressure drop) changes depending on the wall friction and solid acceleration. If the upstream solid loading ($G_s/U_g/\rho_g$) is far away from the solid loading at the inflection point, the uneven solid distribution in the pair of cyclones could be limited although there exists uneven gas–solid flow in the riser. If the upstream solid loading is almost equivalent to the solid loading at the inflection point, the wall friction and solid acceleration both significantly influence the mal-distribution, and the solid distribution in the cyclones would be much more non-uniform compared with the dilute phase and the dense phase.

## 1. Introduction

Due to the high collection efficiency, simple structure and low cost, cyclone is widely used to separate the entrained solids from the flue gas in circulating fluidized beds (CFB). As shown in Fig. 1 [1], multiple identical cyclones are parallel placed in the CFB boilers with huge capacity. The layout of parallel cyclones could be better to handle the huge flue gas flux compared with the single cyclone, and give better collection efficiency. The uniform distribution of gas–solid flow in the parallel cyclones are assumed to get the optimized cyclone structure during the design process, however the uneven distribution is often identified during the operation. The uneven distribution in parallel cyclones is similar to the uneven distribution of gas–liquid flow in parallel paths as shown in Fig. 2 [2]. The uneven distribution of multi-phase flow in parallel pathways, which is called as the mal-distribution, is the unique characteristic compared with the single-phase flow.

The mal-distribution in parallel cyclones has detrimental effects on the performance of CFB boliers. Stern et al. [3] compared the collection efficiency between the multiple cyclones in parallel and the single cyclone at the same operating condition, and found that the parallel system obtained lower collection efficiency. In addition, the difference of collection efficiency between the single cyclone and the parallel cyclones increases with the increase of cyclone number [3]. The similar reduction in collection efficiency was found by Koffman [4]. The reduction results from the deviation of operating condition from the optimum condition. Part of cyclones operate below the optimum condition, corresponding to the optimum collection efficiency, and others operate above because of the mal-distribution. Besides, publications reported the mal-distribution may lead to different fouling among the cyclone gas outlets [5] and different wastages of water walls in the riser exit [6, 7]. Different from the sub-critical CFB boilers, the temperature of water wall in the super-critical CFB boilers depends upon the heat flux density which is related to the distribution of gas–solid flow in the riser exit. Therefore the uneven gas–solid flow into cyclones caused by the mal-distribution may bring dangers to the hydrodynamic security in the super-critical CFB boilers [8].

Grace et al. [9] proposed the theory for the gas–solid flow in multiple parallel cyclones. For the system of N cyclones in parallel, 2 N unknowns and N + 1 controlling equations make the system has N − 1 degrees of freedom, indicating a series of solutions. The extra freedoms give the theoretical explanation for the mal-distribution in practice. Based on this theory [9], Masnadi et al. [5] analyzed the effect of upstream solid loading on the mal-distribution in double parallel cyclones. The calculation shows that the distribution of gas–solid flow in the dense cases are different from those in the dilute cases, however the underlying mechanisms are unclear.

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* Corresponding author.
*E-mail address:* yhr@mail.tsinghua.edu.cn (H. Yang).

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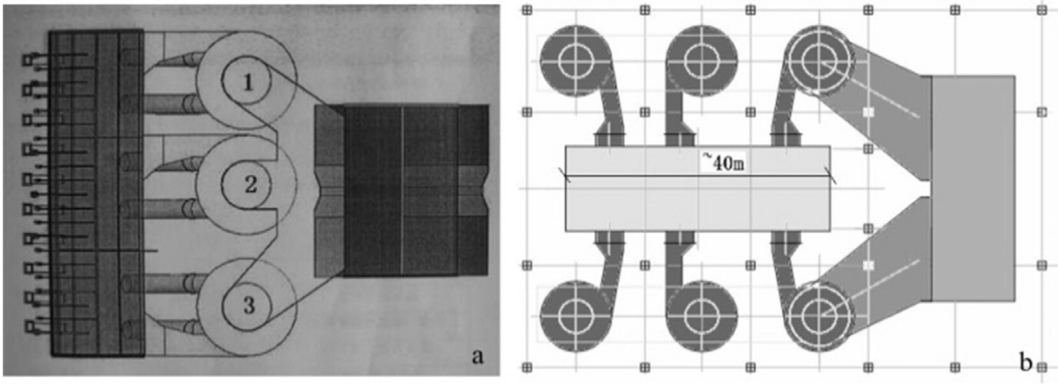

**Fig. 1.** Cyclone layout in CFB boilers (a. 300 MWe, b. 600 MWe) [1].

Experiments related to the mal-distribution in CFB with multiple cyclones are listed in Table 1. In a CFB with three cyclones, Yang et al. [8] found the solid flux in the middle is lower than those in the corners, and the aeration rate in the loop seal influences the deviation of solid flux among the cyclones. Similar phenomenon were observed in the CFB with six parallel cyclones [10–12]. In summary, the mal-distribution is influenced by the fluidizing gas velocity, the system inventory and the aeration rate in the loop seal. The solid loading in the riser exit may substantially influence the distribution of gas–solid flow, and the mal-distribution in the dilute solid loading would be different from that in the dense solid loading [5]. The solid loading in the riser exit depends upon the solid circulation rate and the fluidizing gas velocity. As shown in the Table 1, it is evident that the solid loadings in the experiments are relatively low due to the low solid circulation rates.

Although the mal-distribution of gas–solid flow through parallel cyclones may be caused by the core-annular flow and the pulsation of gas–solid flow in the riser, the gas–solid flow would tend to meet the identical pressure drop due to the same inlet and outlet for gas flow, which indicate that the cyclone may re-distribute the gas–solid flow. For example, the uneven gas flow with the uniform solid flow would not meet the pressure drop constraint, and the solid flow would be re-distributed to meet the pressure drop constraint. The re-distribution depends upon the effects of solid loading on the cyclone pressure drop at certain inlet gas velocity. The solid flow influences on the cyclone pressure drop by the wall friction and the solid acceleration [13–15]. The solid strands descending along the cyclone wall enhance the friction between the gas–solid mixture and the wall, leading to the decrease of tangential velocity of the mixture and the decrease of pressure drop [13]. Since the flow channel shrinks at the inlet of cyclone, the gas velocity increases substantially, and the entrained solids would get extra momentum to accelerate. The increase of momentum depends upon the solid loading. For the dense solid loading, more momentum for solid acceleration would lead to the greater pressure drop. It should be noticed that the solid acceleration would not just happen at the inlet. For the solids with small size, the majority of acceleration may exist at the inlet, however the solids with great size would still accelerate in the cyclone body. The wall friction and solid acceleration both enhance with the increase of solid loading, leading to the non-linear variation of pressure drop [16]. In the dilute solid loading, the main contribution for the pressure drop is the wall friction, leading to the decrease of pressure drop compared with pure gas flow [15]. However the solid acceleration becomes the main contributor to the pressure drop in the dense solid loading [15], and the pressure drop increases with the solid loading. The different effects of solid flow on the pressure drop may explain the mal-distribution differences between the dilute and dense solid loadings.

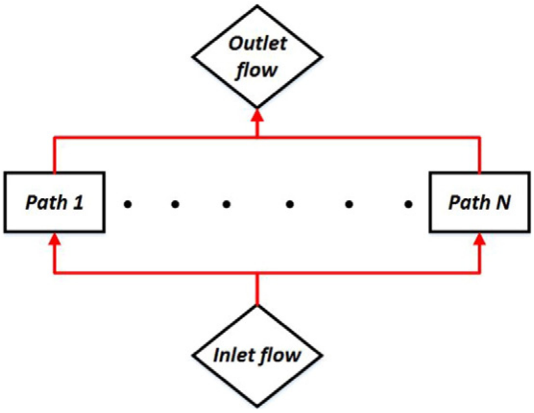

**Fig. 2.** Schematic diagram for flow through N parallel paths [2].

Based on the theory proposed by Grace [9], this paper analyzed the effects of the wall friction and the solid acceleration on the mal-distribution of gas–solid flow through double identical cyclones in parallel, and effects of cyclone structures and the inlet gas velocity on the wall friction and solid acceleration were discussed.

## 2. Theoretical consideration

For the industrial-scale CFB with double cyclones, the solid loading in the riser exit, namely the upstream solid loading ($C_s$), is almost $G_s/\rho_g/U_g$, and the inlet solid loadings ($C_i$) of the cyclones are set as:

$$C_{i\_1} = \frac{\gamma G_s}{\sigma \rho_g U_g} \tag{1}$$

$$C_{i\_2} = \frac{(1-\gamma) G_s}{(1-\sigma) \rho_g U_g}. \tag{2}$$

The same inlet and outlet between the cyclones make the parallel cyclones have the identical pressure drop.

$$\Delta P_{c\_1} = \Delta P_{c\_2} \tag{3}$$

With the increase of the inlet solid loading, the cyclone pressure drop experiences non-linear change, and an inflection point has been widely confirmed in the literature [14,16–19]. The inflection point distinguishes effects of the solid flow on the pressure drop, and the solid loading at the inflection point is defined as $C_{s\_in}$. When $C_i$ is smaller than $C_{s\_in}$, the effect of wall friction takes the main contributor. If $C_i$ is greater than $C_{s\_in}$, the solid acceleration becomes the main influencing factor.

The non-linear characteristic caused by the wall friction and solid acceleration is of significance to the investigation on the mal-distribution. The universal model proposed by Chen et al. [20] could show the two effects, while $C_{s\_in}$ calculated by the universal model is too small [16].