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Experimental research on the unstable performances of parallel external loops in the circulating fluidized bed

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ABSTRACT

Severe pressure fluctuations in parallel external loops were found in the circulating fluidized bed (CFB) boilers recently, so a CFB test rig with two external loops was established to investigate the unstable performance of parallel external loops. A long-length horizontal section was used in the loopseal to intensify the impact of gas flow inside horizontal section on solid circulation rate, and CO_2 tracer method was used to detect the variation of gas flow rate in the horizontal section. The results showed that the solid circulation rate would significantly influence the performance of parallel external loops. The pressure drop in the parallel external loops at low solid circulation rate was relatively stable if aeration air distributed evenly between the two parallel external loops, and the high-frequency pressure fluctuation in the riser was ascribed to the bubble behavior at turbulent fluidization. However, the fluctuation of gas flow rate inside the horizontal section aggravated at high solid circulation rate, leading to the unstable solid recycling rate, as well as the low-frequency and high-amplitude fluctuation of pressure drop in the parallel external loops. For this reason, a single blower is not recommended to use to supply the aeration rate among parallel external loops.

1. Introduction

A typical external loop in a circulating fluidized bed (CFB) reactor consists of a cyclone to separate the gas–solid mixture, a standpipe to provide the driving force for solid recycle and a loop-seal to convey the solids back to furnace. Nowadays the multiple parallel external loops are widely adopted in the large-scale CFB boilers (Yue et al., 2009; Hotta, 2009; Li et al., 2009a), which can ensure sufficient separation efficiency in the case of huge flue gas flux and increase the uniformity of solid distribution at the bottom furnace. The number of parallel external loops depends on the boiler load and furnace structure. As listed in Table 1, for a furnace with high width-to-depth ratio, the multiple parallel external loops are customarily placed at the rear side, but for a furnace with pant-leg structure, they are normally symmetrically arranged at the left and right sides. Comparing with the single external loop, the gas–solid flow in the parallel external loops is much more complex. Widely confirmed by industrial practice, a boiler with parallel external loops is much more unstable than that with single external loop. As shown in Fig. 1, the pressure drop fluctuation in the two external loops of a CFB boiler can reach over 10 kPa, accompanying with severe fluctuation of solid circulation rate (G_s). This complicated phenomenon is called the mal-distribution of gas–solid flow among the multiple parallel cyclones (Grace, 2008; Masnadi et al., 2010; Mo et al., 2015). The unstable performance of parallel external loops results in the unstable G_s, thus the solid concentration will fluctuate near the returning port or in the dilute zone. The solid concentration is directly correlated to combustion and heat transfer in the furnace (Cai et al., 2018), so such fluctuation phenomenon is adverse to the stable operation of CFB boilers. Moreover, severe pressure drop fluctuation in the standpipes may cause mechanical damage to the connecting parts in the external loops, and even lead to solid leakage.

Unfortunately, the unstable performance of parallel external loops has not attracted sufficient attention yet. Some industrial practice in China shows that:

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Nomenclature

C_w	CO_2 concentration at the weir top, %
C_s	CO_2 concentration in the standpipe, %
G_s	Solid circulation rate, kg/(m^2 s)
q	Volumetric flow rate of CO_2, m^3/h
Q_a	Aeration rate at the standpipe bottom, m^3/h
Q_f	Fluidizing air flow rate at the weir bottom, m^3/h
Q_h	Gas flow in the horizontal section, m^3/h
Q_v	Gas flow in the standpipe, m^3/h
U_g	Gas fluidizing velocity, m/s
$\triangle P$	Pressure drop, Pa

Subscript

c	Cyclone
dr	Driving force
hs	Horizontal section
r	Riser
sp	Standpipe
w	Weir

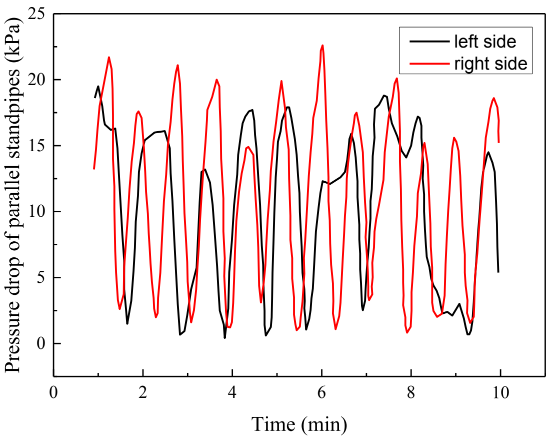

Fig. 1 – The fluctuation of pressure drop in parallel external loops of a 100 MW CFB boiler.

(1) The amplitude of pressure drop fluctuation in standpipe increases with the boiler load.
(2) For a boiler burning high-ash coal, the pressure drop fluctuation in standpipe would be aggravated if the cyclone has excellent separation efficiency.
(3) As shown in Fig. 2, if the CFB boiler is equipped with a single air blower to supply aeration flow into multiple parallel loop-seals, the fluctuation of pressure drop in standpipe would be intensified.

Compared with CFB boilers, the unstable performance in small-scale CFB reactors with single external loop has been thoroughly investigated. In general terms, these studies can be divided into three categories according to the inducing mechanism. Bi et al. (1993) and Bi and Zhu (1993) explained the unstable phenomenon caused by the pressure unbalance in the circulating loop, which is defined as the Type-B choking. The second one is attributed to the influence of bubbles flow in the standpipe. Matsen (1973) proposed an unstable case caused by the bubble rise when the solid downward velocity in standpipe reaches a critical value corresponding to the bubble formation. Zhang and Rudolph (1998) experimentally confirmed such unstable case in the standpipe with an orifice. Srivastava et al. (1998) found a low frequency oscillation of solid volume fraction in the standpipe at the high aeration rate, and explained that the gas bridge in the standpipe caused by the bubble coalescence is responsible for the oscillation. The third type is caused by the multiple fluidization states in standpipe. Leung and Wilson (1973) analyzed the pressure distribution along a standpipe of a commercial catalytic cracking reactor, and inferred that the sudden change from the fluidized state to the packed state above the distributor orifice can cause the unstable performance in the standpipe. The high pressure above the orifice will greatly compress the gas flow, leading to the local defluidizaion, which can be prohibited with the moderate aeration above the orifice to keep stable performance of circulating loop (Bodin et al., 2002). Chen et al. (1984) also confirmed that such unstable behavior in the standpipe is caused by the multiple states. However, the solid flow rate is controlled by the gas–solid flow in the hopper, which is different from the system without the hopper.

A CFB boiler does not have a hopper, and the mechanical valve or the orifice is also replaced by the loop-seal, thus the unstable case in a large-scale CFB boiler is quite different from that in a CFB reactor. Due to the limited lateral solid mixing, uniform gas–solid flow is difficult to realize in a large-scale CFB boiler with large cross section, which will give rise to an irregular phenomenon called the bed overturn (Li et al., 2009b; Li et al., 2010; Wang et al., 2011). The non-uniform gas–solid behavior in the furnace influences G_s, and further intensifies the unstable performance of external loop. Another potential factor causing the unstable performance of external loop may be the huge flow resistance in the loop-seal, especially the flow resistance in the horizontal section of loop-seal. If the length-to-height ratio of horizontal section is small enough, low flow resistance of loop-seal would not cause difficulties in solid recycling (Basu and Butler, 2009). However in a CFB boiler, the long horizontal section limits the solid driving capacity of loop-seal in the dense pneumatic conveying state (Geldart and Jones, 1991; Smolders and Baeyens, 1995). In addition, as shown in Fig. 2, the large-scale CFB boiler normally uses air manifold system to supply the aeration air, so the aeration air distribution among multiple loop-seals would be influenced by the pressure fluctuation in the parallel standpipes, which would intensity the unstable operation.

This paper aims to investigate the unstable gas–solid flow in the horizontal section of loop-seal, and its influence on the unstable performance of external loop in a CFB test rig with two external loops. The horizontal section of the loop-seal has a large length-to-height ratio, therefore the gas–solid flow fluctuation would cause significant impact on solid circulation rate. In addition, one single blower with manifold system is used to provide the aeration flow in the parallel external loops, which may lead to the fluctuation of aeration rate at the standpipe bottoms.

2. Experimental

As shown in Fig. 3, a pair of external loops were symmetrically placed in the cold test rig to recycle solids evenly back to the riser. In order to realize high G_s in the standpipe, the cross-section of riser was designed to be 0.1 m × 0.7 m, and the inner diameter of standpipe was 0.05 m, therefore the cross-sectional ratio between the riser and the parallel standpipes reached to about 18. In addition, the riser height was 3 m, thus strong solid entrainment can be realized even at low fluidizing velocity (U_g). The horizontal section in the loop-seal had a

Table 1 – The layout of parallel external loops in large-scale CFB boilers (Yue et al., 2009; Li et al., 2009a).

	100 MW	300 MW	300 MW	600 MW
Number	2	3	4	6
Position	Rear wall	Rear wall	Left and right wall	Left and right wall
Furnace structure	High width-to-depth ratio	High width-to-depth ratio	Pant-leg structure	Pant-leg structure