Measurement of characteristics of solid flow in the cyclone separators with fiber optical probe

Shaohua Li, Yan Li, Jinjing Li, Shi Yang, Hairui Yang, Hai Zhang, Junfu Lu, Guangxi Yue

Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Thermal Engineering, Tsinghua University, Beijing, 100084 CHINA

lishaohua00@mails.tsinghua.edu.cn, li-y-05@mails.tsinghua.edu.cn, lijinjing00@mails.tsinghua.edu.cn, yangshi07@mails.tsinghua.edu.cn, yhr@mail.tsinghua.edu.cn, haizhang@mail.tsinghua.edu.cn, Lvjf@mail.tsinghua.edu.cn, ygx-dte@mail.tsinghua.edu.cn

Abstract. In some applications, e.g. circulating fluidized beds (CFB), cyclones are usually operated at high solid loadings. Under high inlet solid concentration, most of the particles are collected at the wall and form a dense particle spiral band because of high separation efficiency. As a result, gas-solid reactions should occur mostly in the near-wall region. To understand the gas-solid reaction mechanism in the cyclone, an experimental study was conducted in a plexiglass CFB cold apparatus, with a riser of 0.2m I.D. and 5m high, and a standard Lapple cyclone. Fiber optical probe was used to measure the characteristics of solid flow in the cyclone, including particle velocity and volumetric solid concentration, especially in the near-wall region of the cyclone. Based on the experiment results, the combustion of carbon particles in the cyclone of a CFB boiler was estimated with group combustion theory. The calculated results show that combustion effectiveness factor $\eta_{eff}$ of near-wall particle cloud is smaller than 1/25, which means the combustion rate of a carbon particle in the near-wall region is greatly restricted by other particles in the cloud.

1. INTRODUCTION
Cyclones are widely used as gas-solid separators in the chemical engineering area because of their high separation efficiency, simple structure, good adaptability and low cost. Most of the studies are mainly focused on separation efficiency and pressure drop. A few of them were experimentally (Kessler and Leith, 1991; Patterson and Munz, 1996) or theoretically (Barth, 1956; Mothes and Löffler, 1988) conducted on the gas flow field in the cyclone.

However, gas-solid reactions in a cyclone are also important in many cases, such as when cyclones are used in coal-fired circulating fluidized bed (CFB) boilers (Yue et al., 2006) or the gasifier for fast pyrolysis of biomass (Lede, 2000). But the investigations on gas-solid reactions in a cyclone are very limited.

In CFB boilers and some other applications, cyclones are usually operated at high solid loadings, e.g., 5 kg particles/kg-gas (Muschelknautz and Greif, 1997). Under such conditions, most of the particles are collected at the wall and form a dense particle spiral band because of high separation efficiency. As a result, gas-solid reactions should occur mostly in the near-wall region. The investigation of gas-solid reaction should be based on the knowledge of solid flow behavior in the cyclone. Therefore, well
understanding the characteristics of gas-solid flow, including volumetric solid concentration and particle velocity distribution, in the near-wall region of the cyclone is of particular interest. Nevertheless, the experimental studies on the volumetric solid concentration and velocity distribution of near-wall particles are relatively sparse. The available experimental results on the particle concentration and velocity distribution are mainly obtained in the center of the cyclone when the solid concentration is dilute: Zhou and Soo (1990) measured tangential velocity distribution of particles in the center of the cyclone where the solid concentration was dilute by using Laser Doppler Velocimeter (LDV). Mothes and Löffler (1985) measured the particle concentration distribution at the location relatively far away from the wall ($r/R<0.8$) by probe sampling, where $r$ is the radial distance from the center and $R$ is the cylindrical diameter of the cyclone. Recently, the motion of near-wall particles in the cyclone was experimentally studied. Recently, Chan et al. (2008) used the technique of positron emission particle tracking (PEPT) to determine the particle motion in the cyclone. They found that the average tangential and axial velocity of near-wall particles over the length of the cylindrical body was between 1.5~2.0m/s and 0.9~1.3m/s respectively. However, no volumetric solid concentration of near-wall particles was measured. Muschelknautz and Röper (2008) have made an assumption that the solids velocity near the wall is about several meters per second and the layer thickness is of several millimeters for the CFB boiler condition. However, no experimental data were reported. Fiber optical probe (FOP) has been used for the measurement of particle velocity and volumetric solid concentration by several authors (Johnsson and Johnsson, 2001; Tayebi et al., 1999; Werther, 1999). The fiber optical probes are simple and relatively inexpensive, yield high signal-to-noise ratios and create a minimum disturbance to the flow. They can measure from dilute to dense conditions for different particles in gas or liquid media. And they are more advantageous than some other techniques for the measurements of solid velocity and volume-fraction at the condition of dense gas-solid two phase flow (Tayebi et al., 1999; Zhang et al., 1998; Zhu et al., 2001). Therefore, fiber optical probes are used to measure the volumetric solid concentration and velocity distribution of near-wall particles in this study.

In this research, experiments were conducted to investigate the volumetric solid concentration and velocity distribution of near-wall particles. Based on the experimental results, the combustion of particles in the cyclone of a CFB boiler was estimated with group combustion theory.

2. EXPERIMENTAL

2.1 Experimental System
The cold CFB apparatus is shown in Fig. 1, in which the riser, cyclone, standpipe and loopseal form a circulating loop. Most of the apparatus was made of plexiglass for observation convenience. The riser is 5m in height and 0.2m in inner diameter. The geometry of the cyclone is illustrated in Fig. 2. During the experiments, the fluidizing gas velocity was measured by a vortex flowmeter and controlled by adjusting the damper openness of the valves connected to the forced draft fan and the induced fan. The circulating rate, $G_c$ (kg/s) was measured by weighting the particles accumulation on an electric stop valve installed at the middle of the downcomer in a given time. The pressure drops at different locations of the system were measured by pressure sensors. More details about the experimental system were described in previous studies (Li et al., 2007; Li et al., 2008).

As shown in Fig. 1, several measuring holes were opened at different locations on the cyclone surface, and 3 of them (point 1, 2 and 3) located along the movement direction of particles spiral band in the cylindrical section of the cyclone. The system was operated at required fluidizing gas velocity and initial static bed height. When the system was under the condition of stable fluidizing gas velocity and stable static height of bed material in the downcomer, $G_J$ was measured. Then the volumetric solid concentrations and particles velocities at different radial positions of a measuring point (if it is not specified, the measuring point is point 2 as shown in Fig. 1) in the cyclone were measured by fiber optical probes.
The experimental variables in the present study include gas velocity at the cyclone inlet $V_{in}$ (m/s) and solid concentration at cyclone inlet $C_{s,in}$ (kg/m$^3$). Quartz sand was used as bed material. The values of the process parameters can be found in Tab. 1.

Table. 1 Process parameters

| $d_p$ (mm) | $\rho_b$ (kg/m$^3$) | $\rho_r$ (kg/m$^3$) | $C_{v,0}$ | $V_{in}$ (m/s) | $C_{s,in}$ (kg/m$^3$) |
|------------|----------------------|----------------------|---------|---------------|----------------------|
| 260        | 1550                 | 2650                 | 0.585   | 8.9,13.3,17.4,19.7,22.2 and 25.3 | 2.5~5.7             |

2.2 Fiber Optical Probe System

Fiber optical probe (FOP) was used to measure particle velocity and volumetric solid concentration near the wall in the cyclone. This technique was used in our and some others’ previous studies (Johnsson and Johnsson, 2001; Li et al., 2008; Tayebi et al., 1999). With proper design and application setup, FOP can have high signal-to-noise ratios while with minor disturbance to the flow. Particularly, FOP is more advantageous than other techniques to measure particle velocity and volumetric solid concentration for a dense gas-solid flow (Tayebi et al., 1999; Zhang et al., 1998; Zhu et al., 2001).

The probes used in this study are based on the backscattering principle. The tips of the fiber optical velocity probe and volume-fraction probe both have an outer diameter of 3.8mm. The probes contain thousands of emitting and receiving quartz fibers, each of which has a diameter of 24μm. The velocity probe has two bundles of fibers, and the distance of the bundles, $\Delta x$, is 1.93mm. In each bundle, the fibers are arranged in an alternating array, corresponding to emitting and receiving layers of fibers. The volume-fraction probe has a square area of 2×2mm$^2$ at the center of the tip, in which the fibers are arranged.
The schematic view of the velocity probe can be seen in Fig.3. In the measurement, the probe was inserted into the cyclone with its tip perpendicular to the movement direction of the particles, illuminated a small volume of particles. The two passages of the velocity probe were arranged in the direction of the particle movement and Passage A was in the front, so that one particle passed in front of Passage A first, and after a time delay of $\triangle t$, the particle passed in front of Passage B. The reflected light signals received by each of the passage were converted into an electric signal by a photoelectric converter. And $\triangle t$ was calculated on the basis of cross-correlating the two electric signals with a real-time hardware processor. Then $u_s$ can be calculated by Eq. (1). The detailed measurement principle of the fiber optical probes can be found in the literatures (Chang and Louge, 1992; Werther, 1999).

$$u_s = \frac{\triangle x}{\triangle t} \quad (1)$$

Calibration of FOP is very important. The calibration procedure of the velocity probe is similar to that done by Zhu et al. (2001) and Tayebi et al. (1999). An average-size particle was glued at a radius of $r$ (m) on a thin rotating disk, the surface of which was painted to be black. The disk was driven by a variable speed motor. And the rotational velocities, $n$ (1/s), were measured by a tachometer. Thus, the actual linear velocity of the particle $u_s$ (m/s) is the product of $r$ and $n$. By changing the rotating speed of the disk, different particle linear velocities were obtained. The measured values of $u_s$ with velocity
probe and the actual values were compared as shown in Fig. 4. It can be seen that the measured values were in very good agreement with the actual values.

With a prior accurate calibration, the reflected light intensity received by the volume-fraction probe, i.e., the output voltage was correlated to the volumetric solid concentration, in the form of power function as Eq. (2) (Johnsson and Johnsson, 2001; Tayebi et al., 1999).

\[ U - U_0 = aC_v^k \]  

(2)

Where, \( U \) is measured signal intensity (V) and \( U_0 \) is signal intensity at \( C_v=0 \). \( C_v \) is volumetric solid concentration. \( a \) and \( k \) are constants. The calibration was done in a fixed bed and a dilute region of a well-fluidized bed as the previous works (Chang and Louge, 1992; Lu et al., 2005). For our study, \( k=0.588 \) and \( a=6.55 \).

3. MEASUREMENT RESULTS AND DISCUSSION

In the experiments, under high inlet solid concentration, it was found that solid particles are mostly concentrated in the near-wall particle band, nearly free in the center, and \( C_v \) at different radial locations in the particle band changed with \( V_{in} \) and \( C_{s,in} \). As shown in Fig. 5 and Fig. 6, at the same location, \( C_v \) increases with the increase of \( V_{in} \) when \( C_{s,in} \) is constant, while \( C_v \) increases with \( C_{s,in} \) when \( V_{in} \) is constant. The influence of \( V_{in} \) and \( C_{s,in} \) on \( C_v \) is straightforward. The thickness of the continuous particle band at the wall, \( \delta \) (mm), is defined as the distance from the wall where \( C_v=0.01 \). Shown in Fig. 5 and 6, \( \delta \) is in the range of 4-12mm in this experiment, validating the assumption of Muschelknautz and Röper (2008).

It is worth to point out for the cyclone used in the CFB boiler, the width of the cyclone inlet is much larger than that in current experiments. Thus, for the same \( C_{s,in} \), the thickness of the particle band could be much larger, even in one order.

The radial distributions of near-wall particle velocity \( u_r \) were measured under different \( V_{in} \) and \( C_{s,in} \). Since the radial velocity of near-wall particles was very small, \( u_r \) was the resultant velocity of tangential velocity and axial velocity. Fig. 7 shows that radial distribution of particle velocity under different \( V_{in} \) and \( C_{s,in} \) are similar: \( u_r \) first decreases then increases with the increase of \( L \). And \( u_r \) is in the range of 0.5~2.5m/s. The range of \( u_r \) is similar to that of Chan et al. (2008). The results of this study confirm the assumption of Muschelknautz and Röper (2008).

According to the results of Chan et al. (2008), the near-wall particles’ average tangential velocity over the length of the cyclone body was not obviously influenced by the change of \( V_{in} \) and \( C_{s,in} \). Based on
our previous study (Li et al., 2008), particle average residence time in the cyclone is nearly constant. Therefore, it is expected that the near-wall particles’ average axial velocity over the length of the cyclone body is also inappreciably influenced by the change of \( V_{in} \) and \( C_{s,in} \). In this study, the mass-based average velocity at point 2, \( \overline{u_s} \), is in a small range of 1.5~2.5m/s. Thus, \( u_s=2m/s \) is proposed for the estimation of gas-solid reaction in the near-wall region of a cyclone. The detail influences of \( V_{in} \) and \( C_{s,in} \) on \( u_s \) at different positions need to be investigated further.

Figure 7. Particle velocities at different distances from the wall

The measured volumetric solid concentration \( C_{v,i} \) and particle velocity \( u_{s,i} \) can be validated through circulating rate \( G_s \).

\[
G_s = \sum_{i=1}^{k} l_i W \rho_s u_{s,i} C_{v,i} \tag{3}
\]

In Eq. (3), \( k \) is the total number of measuring intervals the probe moved along the radial direction; \( l_i \) is the distance interval the probe moved in each step, in our study \( l_i=1mm \); \( W \) is the width of the particle spiral band, which is about 0.2~0.3m in the present experiment. \( u_{s,i} \) (m/s) and \( C_{v,i} \) correspond to the particle velocity and volumetric solid concentration measured in the \( i \)th step.

For the conditions that \( V_{in} =17.4m/s, C_{s,in} =4.51kg/m^3 \) and \( V_{in} =25.3m/s, C_{s,in} =5.06kg/m^3 \), the calculated \( G_s \) are 0.73kg/s and 1.40kg/s respectively, while the measured values of \( G_s \) are 0.78kg/s and 1.27kg/s respectively. It can be seen the experimental results agree well with the theoretical calculations.

4. COMBUSTION OF PARTICLES IN A CYCLONE OF A CFB BOILER

Group Combustion theory (Annamalai et al., 1994) can be used to estimate the combustion of carbon particles in a cyclone. While the temperature is higher than 1000K, \( 2C+O_2=2CO \) is the primary reaction for carbon combustion (Law, 2006). Since the ambience temperature in the cyclone of a CFB boiler is about 1200K, single film model can be used to estimate carbon combustion (Annamalai et al., 1994). For single film model, the combustion of particle cloud is divided into several stages, which can be seen in Tab.2: If the cloud is very dilute, the burning rate of each particle is the same as that of an isolated particle, this stage is called as isolated particle combustion (ISOC). With the increment of number density, the particle cloud undergoes the stages of interactive combustion and then partial group combustion. When the number density is very large, the oxygen mass fraction at the cloud surface approaches zero, and the entire cloud can be treated as a single large particle with the density the same as the cloud mass density. This stage is called sheath combustion.
In Tab. 2, group combustion number $G'$, is defined as the ratio of transport rate between the particles in the cloud to transport rate between the cloud and ambience.

| $G'$ | Combustion stage of particle cloud |
|------|-----------------------------------|
| $< 0.3$ | isolated particle combustion |
| $0.3 < G' < 9$ | interactive combustion |
| $9 < G' < 100$ | partial group combustion |
| $G' > 100$ | sheath combustion |

According to the experimental results, the particles are nearly free in the center of the cyclone, e.g. the particles number density is very small in the center. Consequently, in the cyclone of a CFB boiler, the combustion of carbon particles in the center region can be treated as isolated particle combustion.

For using group combustion theory to estimate the near-wall particles’ combustion in the cyclone of a CFB boiler, the following simplification and assumption should be made:

(1) In fact, bed material in a CFB boiler is a mixture of carbon particles and inertia particles, and the ratio of carbon particles, $f$, is as small as 2%~5%. $f = 3\%$ is used for the estimation.

(2) Near-wall particles cloud can be simplified as a slab, whose character length is the thickness of the band, $\delta$.

(3) It is assumed the near-wall particles cloud is monosized, which means the diameters of particles in the cyclone are the same.

(4) To simplify the estimation, it is assumed that the near-wall particles cloud is uniform, e.g. the volumetric solid concentration at different locations in the near-wall particle band equals to the average value of volumetric solid concentration, $1 - \varepsilon$. In fact, according to our experimental results, the distribution of volumetric solid concentration is not even.

(5) Near-wall particles cloud is isothermal.

The species conservation equation of oxygen can be written as Eq. (4). $S_{V,C}$, the surface area of particles per unit volume, can be calculated with Eq. (5). $R_{ch}$ and $R_{d}$, which can be calculated with Eq. (6) and (7), are chemical resistance and diffusion resistance respectively. Because the diffusion resistance of oxygen to the surface of near-wall particle cloud can be omitted, only the diffusion resistance of oxygen in the particle cloud is considered.

For a slab particle cloud, Eq. (4) is converted to Eq. (8). Using $\xi = L / \delta$, $\Phi = Y_{O_2}/(Y_{O_2})_C$ to simplify Eq. (8), we can get a second-order linear differential equation Eq. (9). The expression of $G'$ and $G$ can be seen in Eq. (10) and (11). $\Phi$ in Eq. (12) is the solution of Eq. (9).

$$\nabla \cdot (\rho D \nabla Y_{O_2}) = m_{O_2} = S_{V,C} Y_{O_2} / (R_{ch} + R_d)$$  \hspace{1cm} (4)

$$S_{V,C} = \pi d_p^2 M = \frac{6(1 - \varepsilon)}{d_p}$$  \hspace{1cm} (5)

$$R_{ch} = \frac{1}{k \rho}$$  \hspace{1cm} (6)

$$R_d = \frac{f d_p}{\rho Sh_p D}$$  \hspace{1cm} (7)
\[
\frac{d}{dL} (\rho D dY_{O2} / dL) = S_{v,c} Y_{O2} / (R_{ch} + R_d) \quad L < \delta \quad (8)
\]

\[
\frac{d^2 \Phi'}{d\xi^2} = G' \Phi' \quad \xi < 1
\quad (9)
\]

\[G' = G / (1 + \frac{Sh_p D}{fkd_p}) \quad (10)\]

\[G = S_{v,c} \delta^2 Sh_p / (f d_p) \quad (11)\]

\[\Phi' = \cosh[(G')^{\frac{1}{2}}] / \cosh[(G')^{\frac{1}{2}}] \quad (12)\]

\[\eta_{eff} = \int_{0}^{\delta} \frac{m_{O2,c}}{m_{O2,c}} dL = \int_{0}^{\delta} \frac{A 4\pi Md_c Y_{O2}}{A \delta^4 \pi Md_c Y_{O2,c}} dL = \frac{\tanh[(G')^{\frac{1}{2}}]}{(G')^{\frac{1}{2}}} \quad (13)\]

In Eq. (13), \(\eta_{eff}\), combustion effectiveness factor, is the average ratio of reaction rate of particles in the cloud to that of particle at cloud surface. Therefore, provided that \(G'\) is calculated, combustion of near-wall particle cloud in the cyclone of a CFB boiler can be estimated. Then, we use the experimental results and group combustion theory to estimate the near-wall particle combustion in a cyclone of a 135MWe CFB boiler. The dimensions of the cyclone can be found in Tab. 3.

| D (m) | h (m) | H (m) | a (m) | b (m) | S (m) | De (m) | B (m) |
|-------|-------|-------|-------|-------|-------|--------|-------|
| 8.35  | 10.45 | 23    | 6.7   | 2.7   | 6.4   | 3.67   | 3     |

Table. 4 Process parameters of the cyclone of a 135MWe CFB boiler

| \(d_p\) (\(\mu m\)) | \(f\) | \(u_s\) (m/s) | \(D\) (m/s) | \(k\) (m/s) | \(T\) (K) | \(V_{in}\) (m/s) | \(G\) (kg/s) | \(W\) (m) |
|-----------------|-----|---------|---------|---------|--------|-------------|-------------|------|
| 100             | 3%  | 2       | 2.15e-4| 0.031   | 1173   | 25          | 340         | 8.1  |
| 0.99            | 2650| 1.31    | 0.71   | 2.61    | 0.1    | 0.922       | 6500        | 1.24%|

\[Sh_p = 2 + 0.6 \text{Re}_{p}^{\frac{1}{2}} \text{Se}_{p}^{\frac{1}{2}} \quad (14)\]

\[\delta = \beta \frac{0.008b}{0.0705} \quad (15)\]

\[\eta G_e = C_{s,in} V_{in} ab = W \delta u_s \rho_p (1 - \bar{e}) \quad (16)\]
The process parameters of this cyclone are shown in Tab. 4. Since $0<\Re_p<200$, $Sh_p$ can be calculated with Eq. (14). Eq. (15) is used to calculate $\delta$ in the cyclone of the 135MWe CFB boiler. In Eq. (15), $b$ and 0.0705 are the inlet widths of cyclones in the 135MWe boiler and experimental system respectively. 0.008m is the average value of $\delta$ in our experiment. $\beta$ is correction coefficient and $0<\beta<1$. $\varepsilon$ can be calculated with Eq. (16). In Eq. (16), $W$ is assumed to be 8.1m.

The corresponding values of $G'$ and $\eta_{eff}$ under different value of $\delta$ and $\varepsilon$ can be seen in Fig. 8. Since $G'>>100$ and $\eta_{eff}$ is very small, the near-wall particles in the cyclone of the 135MWe CFB boiler are in sheath combustion stage. The results indicate that the agglomeration of particles at the near-wall region in the cyclone of a CFB boiler prevent oxygen diffusion into the particle cloud and greatly hinder the combustion of carbon in the near-wall particles.

![Figure 8. Values of $G'$ and $\eta_{eff}$ under different value of $\delta$.](image)

5. CONCLUSION

In this study, the distributions of volumetric solid concentration $C_v$ and particle velocity $u_s$ in the near-wall region of a cyclone were experimentally investigated. Then the combustion of particles in the cyclone of a CFB boiler was estimated. Following conclusions are drawn:

- The $C_v$ is higher at the positions closer to the wall. It increases with the increment of gas velocity or solid concentration at cyclone inlet. The particle band in the cylindrical part of the cyclone is about 4-12mm thick under present experimental conditions.
- The velocity of near-wall particles is in the range of 0.5~2.5m/s. Its average value over the cyclone body is insensitive to the operation parameters. $u_s=2$m/s is proposed to be used in the estimation of gas-solid reaction in the near-wall region.
- Based on the experimental results, group combustion theory is used to estimate the combustion of near-wall particles in the cyclone of a 135MWe CFB boiler. It is found that the reaction rate of carbon and oxygen in the near-wall region is smaller than 1/25 of the reaction rate of the particle at cloud surface.

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NOMENCLATURE

- $a$: coefficient in the calibration function (Eq. (1)) [-]
- $A$: surface area $[m^2]$
C_{s,in}  solids concentration at cyclone inlet  [kg/m^3]
C_V  volumetric solid concentration  [-]
C_{V,0}  volumetric solid concentration in a fixed bed  [-]
D  diffusion coefficient  [m^2/s]
d_p  mean diameter of particles  [\mu m]
G  group combustion number  [-]
G_a  circulating rate  [kg/s]
k  chemical reaction rate constant  [m/s]
L  distance from the wall  [mm]
M  number density  [-]
\dot{m}_O_2  consumption rate of oxygen  [kg/m^3-s]
n  rotational velocity  [1/s]
r  radial distance of the particle to the center  [m]
R  cylindrical diameter of cyclone  [m]
S_{V,C}  surface area of particles per unit volume  [m^2/m^3]
T  ambience temperature in a cyclone  [K]
u_{g,s}  gas-solid slip velocity  [m/s]
u_s  particle velocity  [m/s]
\bar{u}_s  mass-based average velocity of near-wall particles  [m/s]
U  measured signal intensity  [V]
U_0  measured signal intensity at \( C_v = 0 \)  [V]
V_{in}  gas velocity at cyclone inlet  [m/s]
W  width of the particle layer  [m]
Y  gas phase mass fraction  [-]
Sh_p  particle Sherwood number  [-]

\textbf{Greek Letters}
\delta  thickness of the continuous particle layer at the wall  [mm]
\varepsilon  average value of voidage of near-wall particle cloud  [-]
\eta  separation efficiency  [-]
\eta_{eff}  combustion effectiveness factor  [-]
\rho  particle group density  [kg/m^3]
\rho_b  bulk density of particles  [kg/m^3]
\rho_r  real density of particles  [kg/m^3]

\textbf{Subscripts}
c  cloud surface
ch  chemical
d  diffusion
g  gas
in  cyclone inlet
p  particle
s  solid

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