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Multicriteria optimisation of first-stage cyclones in the clinker burning system by means of numerical modelling and experimental research

Marek Wasilewski [a,*], Jerzy Duda [b]

[a] Faculty of Production Engineering and Logistics, Opole University of Technology, 76 Proszkowska St., 45-758 Opole, Poland
[b] Institute of Management and Production Engineering, University of Applied Science in Nysa, 7 Armii Krajowej St., 48-300 Nysa, Poland

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ABSTRACT

Multiphase flow inside first-stage cyclones in the clinker burning system was analysed and described based on numerical and experimental research methods. The research was preceded by operation tests on two industrial installations. This allowed for the reproduction of real operation conditions and the construction of the research station. In total, 57 geometric configurations of cyclone separators were studied. Data collected from calculations of computational fluid dynamics (CFD) and laboratory tests were compared in order to determine the reliability of the obtained results.

The presented methods of analysis of flow inside the apparatus helped prepare design guidelines for first-stage cyclones used in clinker burning. The proposed guidelines enable the design of high-performance cyclones for specific operating conditions of a given installation depending on the objective function adopted in the design optimisation process. Furthermore, the proposed structural changes may be applied in traditional cyclone dust separators as a solution to the continuously decreasing allowable limits of dust concentration in atmospheric emissions.

1. Introduction

Cyclones are among the most popular mechanical dust separators used to separate solid particles from carrier gas in industrial processes. These devices are used, for example, in the power industry, chemical industry, timber industry, cement industry and manufacturing industry. They have a simple design, low production and operation costs, and almost maintenance-free operation. Additionally, they perform very well in difficult operation conditions, which allows them to be adapted to the specific needs of different systems. They are used for air pollution control and for conducting technological processes (drying, heating and decarbonisation).

In the case of traditional cyclone dust separators, the main parameters determining their performance are the efficiency of solid separation and pressure drop. These parameters depend on cyclone geometry and operating conditions. Cyclones are designed mainly based on the results of experimental and model studies. So far, no universal calculation method has been developed that would provide fully consistent results with studies of different types. Nevertheless, theoretical analysis of phenomena occurring inside the cyclone based on physical observations allows the relationships between design parameters and cyclone efficiency to be determined. However, one must remember that due to the complex nature of the flow inside the apparatus, a full description of the phenomena can only be obtained by means of experimental research [1–3].

The pioneers of analytical methods aiming to determine the efficiency of cyclone dust separators were Lapple [4] and Barth [5]. Cyclone efficiency has been the subject of numerous experimental and theoretical works that can be classified according to the applied research method:

1. Analytical methods:

- Theoretical and semi-empirical models were developed by many researchers, including Shepherd and Lapple [6], Alexander [7], First [8], Stairmand [9], Barth [5], Avci and Karagoz [10,11], Zhao [12], Chen and Shi [13] and Muschelknautz [1–3], among others.
- Statistical models: In the 1980s, statistical modelling was proposed as an alternative to cyclone studies. For example, models proposed by Casal and Martinez [14], Dirgo [15] and Coker [16] were developed using multiple regression analysis based on larger data sets for various cyclone configurations.

* Corresponding author.
E-mail addresses: m.wasilewski@po.opole.pl (M. Wasilewski), jerzyduda@onet.eu (J. Duda).

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Nomenclature

a	height of the gas inlet, m
b	width of the gas inlet, m
B	diameter of the cyclone lower (dust) outlet, m
C_D	drag coefficient
CFD	computational fluid dynamics
d_p	diameter of a particle, m
D	cyclone body diameter, m
D_e	diameter of the cyclone gas outlet, m
D_{e1}	upper diameter of the cyclone gas outlet, m
D_{e2}	lower diameter of the cyclone gas outlet, m
DPM	discrete phase model
D_{ij}	the stress diffusion term
F	area of cyclone inlet, m^2
F_k	momentum transport coefficient, t^{-1}
g	acceleration of gravity, m s^{-2}
h	height of the cyclone cylindrical section, m
H	total height of the cyclone, m
H_c	height of the cyclone conical section, m
k	turbulence kinetic energy, m^2 s^{-2}
P	pressure, Pa
P_{gi}	pressure of gas phase (i cyclone degree of the suspension preheater), Pa
P_{ij}	the shear production term
PRESTO	Pressure Staggering Option
p′	dispersion pressure, Pa
Q_i	inlet gas volumetric flow rate, m^3 s^{-1}
r_e	distance between the cyclone axis and inlet axis, m
RANS	Reynolds average Navier–Stokes
Re	Reynolds number
RSM	Reynolds stress model
s	the source term
S	height of the outlet duct in the interior of the cyclone, m
SIMPLE	semi-implicit method pressure-linked equations
T_{gi}	temperature of gas phase (i — cyclone degree of the suspension preheater), K
T_{si}	temperature of raw meal (i — cyclone degree of the suspension preheater), K
t	time, s
u	gas velocity, m s^{-1}
$u'_{i\ (j,\ k)}$	fluctuating velocity to direction i (j, k)
u_p	particle velocity, m s^{-1}
α_g	angle of the cyclone inlet head, degree
ΔP	pressure drop in a cyclone separator, Pa
δ	Kronecker factor
ε_{ij}	the dissipation term
μ	dynamic viscosity of gas, kg m^{-1} s^{-1}
Π_{ij}	the pressure-strain correlation term
ρ	density of gas, kg m^{-3}
ρ_p	density of a particle, kg m^{-3}
τ_{ij}	the Reynolds stress tensor, m^2 s^{-2}

2. Experimental studies: Various Studies [17–25] constitute examples of using experimental research methods.
3. Computational fluid dynamics: Various studies [26–47] constitute examples of using CFD for research analyses on cyclone dust separators.

The majority of studies on cyclone separators focus on the determination of dust separation efficiency and pressure drop. A decidedly smaller number of articles focus on the effect of the temperature of flowing media and the shares of individual phases on cyclone efficiency. Bohnet [48,49] and Patterson [50] found that pressure drop and dust separation efficiency decrease with an increase in temperature. This effect is caused primarily by a decrease in gas density and an increase in its viscosity, as was confirmed by Chuah [51] and Gimbun [52] using CFD, and by experimental studies by Li and Chen [53]. The ratio of solid phase to gas phase content plays an important role in the separation process in cyclones. In the case of a large concentration of solid particles, secondary flows at the cycle wall where particles form a dense layer can affect efficiency [54]. For example, Stern [55] found that total dust separation efficiency increases by approximately 35% for a ten-fold increase in dust concentration. Wheeldon and Burnard [56] found that a high solid concentration (50 g/m^3) has a positive effect on the efficiency of cyclone fractional separation.

Both the effect of temperature and the share of individual phases play crucial roles in the optimisation of cyclones included in suspension preheaters in the cement clinker burning process. A suspension preheater (Fig. 1) operates in a similar manner to a classical heat exchanger in the suspension state. The detailed principle of the operation of the device is presented in the paper [57].

Modern suspension preheater systems consist of four to six stages. Cyclones of the subsequent stages of the heat exchanger are designed based on their functions and temperature conditions. The efficiency of a heat exchanger tower can be improved first and foremost by modernising the most important component of the system, i.e. cyclone dust separators (first-stage cyclones). These devices are essential in the operation of a suspension preheater. They should display a high efficiency of raw meal particle separation (>90%). Due to operational conditions during clinker burning, it is not possible to use conventionally designed cyclones. This is due to the large proportion of solid phase (depending on the installation — 300 g/1 m^3 to 700 g/1 m^3). In addition, in the cement industry, the solid phase – the raw meal (whose main component is $CaCO_3$) – is characterized by high fragmentation (it has a large proportion of particles with a diameter of less than 15 μm). In the lower stages of the suspension preheater, it is difficult to ensure high separation efficiency due to an increasing fragmentation of particles (decarbonisation) and low gas density.

2. Experimental setup and methodology

A review of the subject literature and industrial data found that the appropriate shape of individual characteristic components of the structural separator is of crucial importance for the efficiency of cyclone dust separators. Consequently, the authors of this paper focused on research aiming to establish new design guidelines for first-stage cyclones used in the clinker burning system that would allow for the optimisation of their design depending on preset operation conditions. This was possible through the analysis and description of multiphase flow inside the cyclones based on CFD and experimental methods.

2.1. Experimental studies

First, the basic sources of data required that the correct experimental research on the test station be determined. The basic data sources in this study were operation data from two clinker burning systems operating in a cement plant in Poland. A series of measurements was carried out on all system inlets and facility outlets in order to determine the following parameters: mass flows of raw meal, exhaust gas volumetric flows, temperatures of flowing media and pressure drops on subsequent suspension preheater stages. Fig. 2 presents the technological-measuring diagram. A cyclone model and the experimental system were prepared based on the collected data (Fig. 3).

The key component of the research station was the model of a cyclone separator made of transparent plastic (acrylic glass). This