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Analysis of the effects of temperature and the share of solid and gas phases on the process of separation in a cyclone suspension preheater

Marek Wasilewski

Faculty of Production Engineering and Logistics, Opole University of Technology, 76 Proszkowska St., 45-758 Opole, Poland

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ABSTRACT

Most scientific papers discussing cyclone separators do not consider the effects of temperature or the share of the solid and gas phases on the efficiency of such devices. This article analyses the effect of these factors on the efficiency of solid particle separation, based on a cyclone separator that constitutes part of a suspension preheater. The operating conditions for this device allowed for a wide range of temperatures to be taken into account. The main research procedure was preceded by exploitation research conducted at an industrial installation. This enabled the correct reconstruction of the cyclones actual operating conditions. The multiphase flow inside the cyclones was analysed with computational fluid dynamics (CFD). Reynolds-averaged Navier–Stokes equations with the Reynolds stress turbulence model (RSM) were used in the analysis.

The methods used in this paper for analysing the phenomena occurring inside the device allow for the conclusion that both the temperature and the concentration of solid particles have a significant effect on the effectiveness of a cyclone separator. The presented analysis may help to optimise the cyclones used in cyclone suspension preheaters, as well as traditional devices used solely for separation processes.

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1. Introduction

Contemporary industry makes use of many types of cyclone separators due to their universal applicability, simple structure and low exploitation costs. However, no universal cyclone (applicable to any operating conditions) has so far been developed. This is because some devices have a high separation efficiency; whereas others have low exploitation costs (with a minimal pressure drop). The subject literature includes many classifications of cyclones depending on their structure [1–4].

While cyclones are primarily used as typical particulate matter separation devices, they are also often used in technological processes (drying, heating and decarbonisation) that usually involve a high temperature. In such cases, special attention should be paid to the effect of the temperature on the efficiency of the cyclone separator. Furthermore, the share of the solid phase is usually high when compared to the share of the gas phase, due to the fact that the flow of the solid phase directly determines the output of a given installation.

The proposed empirical and semi-empirical models for determining the pressure drop and the efficiency of the particulate separation were developed based on experimental data that were obtained under stable environmental conditions. The majority of experimental studies are also conducted under isothermic and isobaric conditions. The same is true for studies that use a CFD, most of which do not take into account changes in the temperature and pressure. In turn, exploitation data obtained from real industrial installations that operate within a wide temperature range often show considerable discrepancies when compared to computational studies.

Some researchers have already addressed this subject. For example, Bohnet and Lorenz [5,6] noted a considerable effect of temperature on the efficiency of particle separation and on a drop in pressure. They concluded that the decrease in the pressure drop was due to an increase in the temperature, and this could be described by the Meissner equation. Also, the efficiency of the separation was found to decrease with an increase in the temperature. Patterson [7] observed a similar effect of temperature on the efficiency of cyclone separators. He also found that a decrease in the gas density and an increase in the gas viscosity combined with an increase in the temperature had a considerable effect on the results. Gimbun and Chuah [8,9] confirmed these findings using CFD. They also compared the computational models presented by Shepherd and Lapple [10], Dirgo [11], Coker [12] and Casal and Martinez [13]. They indicated that the Shepherd and Lapple model was the most accurate for temperatures in the operating medium

E-mail address: m.wasilewski@po.opole.pl

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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
DPM	discrete phase model
DDPM	dense discrete phase model
D_{ij}	the stress diffusion term
F_k	momentum transport coefficient, t^{-1}
g	acceleration of gravity, m s^{-2}
G_i	mass flow of the particle (solid phase), kg s^{-1}
h	height of the cyclone cylindrical section, m
H	total height of the cyclone, m
k	turbulence kinetic energy, m^2 s^{-2}
N-S	Navier-Stokes equations
P	pressure, Pa
P_{ij}	the shear production term
PRESTO	Pressure Staggering Option
p′	dispersion pressure, Pa
Q_i	volumetric flow rate of the gas phase, m^3 s^{-1}
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_{fi}	temperature of the gas phase (i - zone of the research system)
T_{pi}	temperature of the particle solid phase (i - zone of the research system)
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}

over 500 K; and that the Coker model was best suited to temperatures below 500 K. Bohnet's conclusions were also confirmed in an experimental study by Li and Chen [14]. In turn, Karagoz and Kaya [15] investigated the heat exchange between the solid phase and the gas phase. They noted that the heat exchange increased with an increase in the inlet velocity on all surfaces. Gupta [16] stated that the heat transfer coefficient increased with an increase in the solid substance load and the inlet velocity. Other examples [17–24] offer studies aimed at determining the effect of temperature on the operation of cyclone separators.

Another important factor in particulate separation using cyclones is the ratio between the gas and solid phases. If the solid phase concentration is high, a secondary flux on the walls of the cyclone will have a significant effect on its efficiency [25,26]. For instance, Stern [27] noted that the total efficiency of the separation increased by about 35% with a tenfold increase in the particle concentration. Wheeldon and Burnard [28] also found that the effect of high particle concentration improved the efficiency of the fractional separation in a cyclone. It is worth underlining the fact that most studies conducted so far (regardless of their methodology) have been performed with a low share of the solid phase, i.e. up to 100 g/m^3.

A cyclone suspension preheater that constitutes part of an installation for dry clinker burning is an example of a device in which operating conditions change within a wide temperature range (600–1200 K). The operation of a cyclone suspension preheater is similar to that of a traditional suspension heat exchanger. Modern suspension preheater systems consist of four to six stages. Cyclones of the subsequent stages of the suspension preheater are designed based on their functions and temperature conditions.

Cyclones used for clinker burning are used not only as separators but are also primarily used as regulators for the technological process (decarbonisation), which means that the solid phase flux directly determines the output. Thus, we are dealing with a changing ratio of the solid and gas phases depending on the heat efficiency of the rotary kiln. Today, the share of the solid phase in cement plants across the world ranges from 300 g/m^3 to 900 g/m^3 of the gas phase.

An analysis of the subject literature leads to the conclusion that most studies conducted so far on the development and construction of cyclone separators have focused on traditional cyclone separators; while few have addressed the effects of temperature and the share of each phase on the efficiency of the cyclone's operation. There are few studies on the topic of cyclones used for clinker burning. Examples of this type of research are studies [29–35].

2. Materials and methods

The main aim of this study was to assess the effects of the temperature and the shares of the solid and gas phases on the separation process, based on a cyclone suspension preheater used for clinker burning. As the actual operating conditions had to be simulated as accurately as possible, a series of measurements were conducted prior to the research on a production installation operating in a cement plant in Poland.

2.1. Explanation of the research conditions

The installation comprised a four-stage cyclone suspension preheater and a rotary kiln. The first-stage of the suspension preheater was equipped with four cyclone separators, while the subsequent stages operated as dual systems. The installation also had an additional burning chamber, i.e. a calciner. At its maximal efficiency, the installation processes amounts of about 3500 tonnes/day. Table 1 presents an overview of the measured values for the temperatures and pressures for each factor at each stage. The values for first-stage cyclones are given in italic.

In order to determine the efficiency of the raw material separation by the first-stage cyclones, the mass flow rate of the raw material, the volumetric flow rate of the gases, and the release from the suspension preheater were measured. A mass balance was prepared based on the obtained information. The collected data can be found in Table 2.

Given that the efficiency of a cyclone suspension preheater primarily depends on the first-stage cyclones, subsequent research

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