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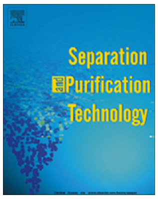

The efficiency improvement of a large-diameter cyclone – The CFD calculations

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ABSTRACT

This paper presents the CFD calculations of a large cyclone (the diameter of the cylindrical part is 0.7 m) equipped with a counter-cone. Three cases of different locations and diameters of the counter-cone base were investigated. The Reynolds-averaged Navier–Stokes equations with the Reynolds stress turbulence model (RSM) were used in the analysis. The Lagrangian method was employed to track the particle motion and calculate the cyclone efficiency. The applied model correctly reflects the flow through the device and facilitates the estimation of the separation efficiency. In the presented case, displacement of the counter-cone into the dust bin improved the separation efficiency with a slight increase in pressure loss.

1. Introduction

Cyclones as centrifugal separation devices have been used by humans for many decades. Extensive use in industry has resulted from their undeniable advantages: a very simple construction and low investment and operating costs. Cyclones would be the best solution almost anywhere if they did not have low separation efficiency. The operating principle of a cyclone – pushing of the particles (grains, drops) of the dispersed phase under the influence of the centrifugal forces of inertia in the direction of the external wall which leads to their separation from the transporting continuous phase (gas or liquid) is used in many different devices. Apart from the basic classification (depending on the type of continuous phase – gas or liquid) of cyclones, into cyclones and hydrocyclones, more types of cyclones may be distinguished. A huge variety of applications provides us with different designs and detailed physical models describing the cyclone performance.

Among many other various applications, cyclones are widely used for gas dedusting. Until recently, they have been extensively used for gas dedusting from coal-fired boilers. However, due to the low efficiency in terms of stopping particles smaller than 5 μm, the role of cyclones along with further dust emission restrictions decreased. Nowadays in Poland, the permissible dust emission from large coal-fired boilers (with a rated thermal input greater than 500 MW) equals 50 mg/m$_n^3$ and is achieved through the use of electrostatic precipitators. In the case of smaller units (5–50 MW) the emission limit is 400 mg/m$_n^3$ and is very often ensured by using cyclone separators. Nevertheless, from 2016 the maximum permissible level of dust emission from these stoker-fired boilers will be reduced to 100 mg/m$_n^3$. Further improvements to the cyclone efficiency are required (and much awaited on by users of old boilers) to ensure that future permissible levels for dust emission are met. The improvement achieved by upgrading an existing installation (at minimal cost) would bring many benefits.

In Poland the CE-type cyclones are used very often at small municipal and industrial heat-generating plants where hard coal is burnt in stoker-fired boilers. These devices were recommended by the relevant standards (such as [1]) for stopping dust (especially that of erosive action) from the flue gases. Apart from industrial and municipal boilers, they have also been used in the foundry and building materials industries. The recommended inlet velocities for the CE-type cyclone range from 8 to 15 m/s. Normalized diameters begin at 0.400 m, with 0.450, 0.500, 0.560 m and so on, up to 1.000 m. In practical applications these devices of smaller diameters are combined into a battery (which consists of two, four, six or more individual cyclones).

Experimental studies of large-diameter cyclones in laboratory conditions are difficult and very expensive. In industrial conditions, such studies are almost impossible. Therefore, the majority of experiments are carried out in small or indeed very small devices. The disadvantages associated with the scale of the device are not in the new area of fluid dynamics referred to as CFD that has been rapidly developing in recent years. In the past several years, a lot of works on the numerical modelling of cyclones have been published. Of all these studies, the publications of Hoffmann and Stein [2] and Cortes and Gil [3] are worth mentioning. The authors in

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question stated that the Reynolds Stress turbulence model (RSM) provides an accurate prediction on flow pattern, axial and tangential velocities and pressure drop in cyclones. For particle tracking – the Lagrangian calculations (one-way coupled) have been commonly used. The LES methods and two-way coupling for particle tracking [4–6] produce results that are closer to the measurements, but are burdened with the multiplication of computational effort and have been less common so far, especially at low mass loads. It may be added that Souza et al. [6] also simulated the cyclone of a diameter of 0.031 m.

Among the more recently published studies the work prepared by Qiu et al. [7] could also be mentioned here. The calculations were applied to a divergent cyclone (diameter of 0.2 m) with 60° counter-cone. The gas flow field is obtained using the RSM, and the particle motion is simulated by the use of the stochastic Lagrangian model with one-way coupling.

In the CE-type cyclone, the diameter of the dust outlet is larger than the diameter of the vortex finder, so it became a natural application of obstruction (e.g. a counter-cone) in the area of the dust outlet. The Branch Standards [1] do not specify the exact location or size of the counter-cone. Although the counter-cone may be quite often met (it is also referred to as a Chinese hat, vortex stabilizer or apex cone), the associated literature of the world does not provide too much information about it (especially when the huge number of publications about cyclones is taken into account). The configuration with the dust outlet which is bigger than the vortex finder inlet may also be found, e.g. in the work of Krambrock [8]. The author in question installed the counter-cone (of a diameter slightly larger than the vortex finder diameter) with the 90° apex angle below the solids outlet. Another apex angle $-120°$ was applied by Muschelknautz and Greif [9]. The counter-cone was placed above the solids outlet (in the conical part of the cyclone). The authors recommend that the radius of the counter-cone should be approximately 0.35–0.40 of the vortex finder radius, and the distance from the counter-cone to the cyclone body should be 0.20–0.40 of the counter-cone radius. The effect of the apex cone shape (i.e. the apex cone angle) on the cyclone cut size was analyzed by Yoshida et al. [10]. The cones of the angles from 40° to 80° were located below the solids outlet. It was found that the optimum apex cone angle is 70°. In another work, Yoshida et al. [11] analyzed the effect of the counter-cone position on the particle classification performance of a cyclone. The apex cone of the cone angle 60° was situated in different positions (in the dust bin) so that the distance (referred to by the authors as apex cone clearance) of the counter-cone base from the edge of the solids outlet varied from 0.012 m to 0.037 m. It was found that the cut size indicates the minimum value for the apex cone clearance from 0.015 m to 0.025 m. In a recent study, Yoshida [12] has shown that increasing the size of the gap (increasing the inlet area to the bin realized by lowering the counter-cone) improves the separation efficiency. Yoshida explains the improvement as the decrease of the average upward fluid velocity, and thus smaller particles tend to go to the dust bin. It seems that it is difficult to say whether this is due to changes in the size of the gap, or changes in distance from the counter-cone to the vortex finder inlet. In all cited cases, Yoshida et al. [10–12] applied a very small cyclone with a diameter of 0.072 m for the purpose of the analysis.

The application of the counter-cone is to some extent associated with the issue of the natural vortex length (many works by Hoffmann have been devoted to this subject recently – [13]). The main function of a counter-cone is to counteract the extension of the end of the vortex downward to the dust bin (when the vortex is too long), and thus prevent the entrainment of some proportion of these solids. From this point of view, the shape of the obstacle is secondary. For example, this could be a flat disc (a plate) that was used by Avci et al. [14] in their analysis of the vortex length. When the vortex is too short, its end (a vortex tail) sticks to the cyclone walls, and this significantly impairs the separation efficiency. The application of the counter-cone as the vortex stabilizer would be a good option in such cases.

Different solutions of a counter-cone were studied by Obermair et al. [15]. The authors in question used both the 90° apex cone located in a dust bin, and the 120° apex cone located above a solids outlet in a cyclone cone. The improvement of the total efficiency by 2% (from 76.8% to 78.8%) with a simultaneous increase in pressure loss of 200 Pa was achieved in the latter case. In their studies, Obermair et al. used the cyclone with a diameter of 0.400 m.

In his previous work, Kępa [16] showed that the efficiency curve (cut size curve) as a function of the distance from the vortex finder inlet to the counter-cone (control surface height) has a minimum $h_{i,ext}$. This minimum depends on the basic geometric dimensions and wall friction coefficient (of dusty gas). For the geometry analyzed (see the next section), $h_{i,ext}$ is approximately 5 m for $\lambda = 0.015$, and nearly 3 m for $\lambda = 0.025$. Thus, it is expected that elongation of the control surface by lowering the counter-cone should improve the cyclone efficiency.

2. Numerical study

This paper presents the results from the calculations for three geometries. The geometry of the first cyclone under analysis which is described in detail in Fig. 1 (geometry A). This cyclone is manufactured by a Polish company and almost all major dimensions are in accordance with the cyclone CE-1-700/0.4 (designation according to [1]). By way of comparison, it may be mentioned that the CE-type cyclone with a body diameter of 0.400 m was simulated in the previous work [17]. The main dimensions of the investigated

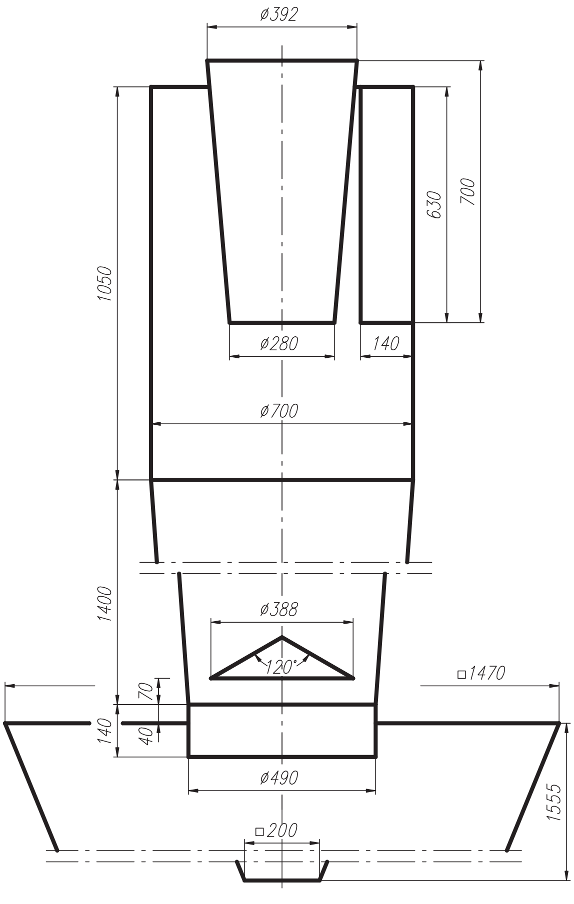

Fig. 1. The geometry of the cyclone (mm) (geometry A).