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Modeling the gas and particle flow inside cyclone separators

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Abstract

This paper reviews the models developed for the flow field inside inverse-flow cyclone separators. In a first part, traditional algebraic models and their foundations are summarized in a unified manner, including the formulae for tangential velocity and pressure drop. The immediate application to the prediction of collection efficiency is also reviewed. The approach is the classical, treating first the dilute limit (clean-gas correlations), and afterwards correcting for ‘‘mass loading’’ effects. Although all these methods have had a remarkable success, more advanced ideas are needed to model cyclones. This is put forward by exploring the work done on the so-called ‘‘natural’’ length of the cyclone, that has led to the discovery of instability and secondary flows. The resort to computational fluid dynamics (CFD) in this case is difficult, however, due to the very nature of the flow structure. A closing section on the subject reviews past and recent CFD simulations of cyclones, both single- and two-phase, steady and unsteady, aiming at delineating the state-of-the-art, present limitations and perspectives of this field of research.
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Keywords: CFD; Cyclone; Gas-solid flow; Swirling flow

Contents

Abbreviations: CFBC, circulating fluidized bed combustion; CFD, computational fluid dynamics; DNS, direct numerical simulation; FCC, fluid catalytic cracking; LDA, laser-Doppler anemometry; LES, large eddy simulation; LRR, Launder, Reece and Rodi implementation of a differential RSTM, also known as the ‘‘basic’’ implementation. Variant: LRRG, after the modification by Gibson and, Launder [91]; PFBC, pressurized fluidized bed combustion; PSD, particle size distribution; PSI-Cell, particle-source-in cell methods of calculation of two-way coupled two-phase flow; PVC, precessing vortex core; RANS, Reynolds averaged Navier–Stokes equations; RNG, Re-normalization group theory; RSTM, Reynolds stresses transport model; SGS, subgrid scale model; SSG, Speziale, Sarkar and Gatski implementation of a differential RSTM [91]; TRANS, transient Reynolds averaged Navier–Stokes equations; equivalent to URANS; URANS, unsteady Reynolds averaged Navier–Stokes equations; equivalent to TRANS.

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1. Introduction

Cyclone separators have been a decisive factor in the development of coal combustion technologies. Among diverse possibilities for hot gas cleaning, these devices have demonstrated the most favorable balance of separation efficiency and cost of investment, operation and maintenance. Able to handle any combination of gas pressure, temperature and very high solids loading, their performance is tolerable as compared with more efficient separation equipment (i.e., ceramic filters), being at once much more simple, robust and reliable. Presently, cyclones are a key component in most advanced coal utilization concepts, such as pressurized and circulating fluidized bed combustion (PFBC and CFBC). In PFBC, cyclones are essential to maintain the integrity of the gas turbine, and thus the advantages of the concept itself [1,2]. In CFBC, the scaling-up of the equipment to sizes compared to conventional coal firing is being developed partly based on new designs of integrated, compact cyclonic separators [3].

As a consequence, there is still a great need of a sound knowledge of the principles of operation. Since cyclones were developed in the last decades of 19th century, extensive experimental work has been done in order to explain their flow characteristics, as a fundamental step to understand pressure drop and separation efficiency. At the same time, and based on the data gathered, theoretical models have been advanced to predict the basic features of the flow field, mostly on semi-empirical grounds. This generic modeling strategy is still in use; in fact, many formulae and methods derived in the past remain very useful indeed for design purposes nowadays. Nevertheless, as in many other fields of study, advances in experimental and computational methods have brought to light many additional details and subtleties of the question.

In the case of cyclone separators, some of them have turned out to be of a rather fundamental nature, and at the same time, of paramount importance from the point of view of applications. Unsteadiness and asymmetry are for example two features not considered in classical cyclone theory that may affect the velocity distribution to a great extent, thus changing the model of the separation mechanism. In close relationship, our picture of the end of the separation vortex has been evolving until very recently. Latest research is revealing that in the vicinity of this region, the flow can be unstable and the vortex can attach to the solid wall, rotating on it. Consequently, the prediction of the total length of the vortex (the so-called "natural length" of the cyclone) is subjected to great uncertainty, as the

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