Journal of Natural Gas Science and Engineering 26 (2015) 313–329

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

journal homepage: www.elsevier.com/locate/jngse

Design and simulation of high pressure cyclones for a gas city gate station using semi-empirical models, genetic algorithm and computational fluid dynamics

Nadimeh Fathizadeh [a], Ali Mohebbi [a, *], Saeid Soltaninejad [b], Masoud Iranmanesh [c]

[a] Department of Chemical Engineering, Faculty of Engineering, Shahid Bahonar University of Kerman, Kerman, Iran
[b] Gas Company of Kerman Province, Research Unit, Kerman, Iran
[c] Energy Department, Institute of Science, High Technology & Environmental Sciences, Graduate University of Advanced Technology, Kerman, Iran

A R T I C L E I N F O

Article history:
Received 15 February 2015
Received in revised form
14 June 2015
Accepted 15 June 2015
Available online 25 June 2015

Keywords:
Natural gas
Black powder
Cyclone separator
Genetic algorithm
Computational fluid dynamics
Grid convergence index method

A B S T R A C T

Solid particles suspended in natural gas pipelines cause many fundamental problems in transmission and distribution network of natural gas. Conducted measurements in the natural gas network of Kerman city, Iran showed a high concentration of black powder in the pipeline. It was found that the current filtration system not to be efficient to remove the solids. Thus, with regarding to the size of black powder, to improve the filtration a cyclone separator before the filtration process was proposed. In this study, the required cyclones for separating black powder from natural gas at high pressure for CGS #1 of Kerman city, Iran were designed. Then, using computational fluid dynamics, simulations were done and their performance evaluated at different conditions. The Reynolds Stress model was used to model the turbulent flow due to existence of swirling flow inside the cyclone. Particle trajectories were calculated by discrete phase model. A high efficiency Stairmand cyclone was selected. To increase the efficiency and prevent direct escapement of particles entering into the cyclone from the internal vortex finder, the vortex length was optimized using Genetic Algorithm (GA). In order to design the cyclone, a number of algorithms were written to calculate the required number of cyclones. The cyclone was designed at pressure and temperature of 1000 psi and 20 °C respectively for maximum capacity of CGS #1 of Kerman city. It is attempted to satisfy the standards of American Society of Mechanical Engineers for pressure vessels in cyclone design. Diameter and thickness of the designed cyclone are 55 cm and 1.125 inches respectively. Simulation validation was done using the Grid Convergence method. The cyclone is able to separate particles with efficiency of more than 96% in summer (the lowest consumption time) and winter (the highest consumption time) well.

1. Introduction

Currently, natural gas is considered one of the main sources of energy for many the developed and developing countries and also be used as a raw material in many industries. Natural gas is produced from gas reservoirs located below the level of land and sea by a proper system is transferred and distributed between the consumers. The gas in different places of transmission and distribution lines always containing some solid particles that is created the pressure drop and will cause damage to the equipment transmission lines and the station (corrosion, abrasion and environmental issues). Suspended solids in natural gas are known as "black powder". These particles are one of the important problems in gas transmission pipelines. To remove these particles from natural gas, a filter-separator or gas cyclone separator is used (Azadi et al., 2012).

Cyclone separators have been used for over 100 years and are still one of the most useful devices to remove solid particles from their carrying fluid flow. Simple design, low cost of construction and maintenance, lack of moving parts and high resistance to difficult operating conditions are the main reasons for significant use of cyclones (Davis, 2000). The centrifugal force created by rotation of the gas in the cyclone causes the particles suspended in the gas, which are denser than it, move toward the cyclone wall (Hoffmann and Stein, 2008). It should be noted that against

* Corresponding author.
E-mail addresses: amohebbi2002@yahoo.com, amohebbi@uk.ac.ir (A. Mohebbi).

http://dx.doi.org/10.1016/j.jngse.2015.06.022
1875-5100/

apparent simplicity of cyclones, their flow and collection characteristics are complex and the cyclone performance is influenced severely by any change in geometrical dimensions and operating conditions (Azadi et al., 2010).

The collection efficiency and pressure drop are two main performance characteristics of the cyclone separators (Azadi and Azadi, 2011). A slight change in the dimensions of cyclone can improve its performance. For predicting the performance of a cyclone, many mathematical models have been developed such as Lapple theory(1951), Barth theory (1958), Sproull theory(1970), Lieth and Licht theory(1972) (Davis, 2000). Most of them are based on empirical or semi-empirical equations. The conventional method for predicting the flow field in a cyclone and its performance is empirical (Wang et al., 2006). Nowadays, the Computational Fluid Dynamics (CFD) method is a promising tool to investigate the flow field behavior and performance of a cyclone. Boysan carried out one of the first CFD simulations (Boyson et al., 1986). He realized that the standard k−ε turbulence model is not appropriate to simulate swirling flow inside a cyclone due to excessive turbulence viscosities and insubstantial tangential velocities.

Many researches have been performed for improving the performance of a cyclone and specifying the flow field behavior (Azadi and Azadi, 2011). Gimbun et al. (2005) investigated impact of cone tip diameter on cyclone performance by CFD simulation and concluded that the reduction of the diameter increases the efficiency and pressure drop (Gimbun et al., 2005). Zhao et al. (2006) simulated the gas flow field in a new type of cyclone with the spiral double inlets. Their results showed that the new cyclone improves the symmetry of gas flow pattern and enhances the efficiency of particles separation (Zhao et al., 2006). Swamee et al. (2009) optimized the diameter of cyclone body and vortex finder for a set of parallel cyclone. This was done for a specified gas flow rate and cut-off diameter. For calculating pressure drop and cut-off diameter, they used Stairmand model and the Gerrard and Liddle formula respectively (Swamee et al., 2009).

Azadi et al. (2010) used a CFD model to study the effect of cyclone size on its performance. Their results indicated that the cyclone cut-off diameter and pressure drop increase as the cyclone size increases (Azadi et al., 2010). Elsayed and Lacor (2010) modified the dimensions of Stairmand model slightly. They showed that the pressure drop of new cyclone is less than Stairmand cyclone and decreases approximately to half (Elsayed and Lacor, 2010). Safikhani et al. (2011) carried out a multi-objective optimization on cyclones. First, for obtaining the pressure drop and cut diameter, flow through cyclones was simulated. Then an artificial neural network was used to calculate the objective function value and finally, by using multi-objective genetic algorithms they improved the efficiency of the cyclone (Safikhani et al., 2011).

Su et al. (2011) simulated the gas–solid flow in square cyclone separators with three types of inlet configuration. They analyzed the effect of inlet configurations on the turbulent dynamics in the cyclone and the separation efficiency and pressure drop. Their results showed that three dimensional Reynolds Stress Model (RSM) was suitable to predict the swirling suspension flow in the square separator. The separators with double declining inlets and single normal inlet had the minimum pressure drop and the best separation efficiency respectively (Su et al., 2011). Gong et al. (2012) studied the gas flow in an axial flow cyclone separator based on the RNG k-ε model combined with the Reynolds stress model. They analyzed the effects of helix angle and leaf margins on the internal flow field of the cyclone. Their simulation results showed that the pressure drop of the cyclone increases with decreasing the helix angle and the effect of the leaf margins can be neglected (Gong et al., 2012). Elsayed and Lacor (2013) performed a multi-objective optimization study of a gas cyclone separator by using the response surface methodology (RSM) and CFD results. They investigated the effects of the inlet height, the inlet width, the vortex finder diameter and the cyclone total height on the cyclone performance. Their results showed a strong interaction between the inlet dimensions and the vortex finder diameter. However, there was no interaction between the cyclone height and the other three factors. Finally, they concluded that the artificial neural networks can offer a powerful approach to predict the cyclone performance than the response surface methodology (Elsayed and Lacor, 2013). Shukla et al. (2013) investigated the effect of modeling of velocity fluctuations on the prediction of collection efficiency of cyclone separators by using the Reynolds stress turbulence model (RSTM) and large eddy simulation (LES). Their results suggested the simulation of velocity fluctuations in cyclones has a great effect on the prediction of collection efficiency, especially for small particles. Moreover, they showed LES has good accuracy on prediction of both the mean and fluctuating flow fields (Shukla et al., 2013).

Gao et al. (2014) investigated the effects of the central channel parameters on the flow field in five cylinder-shaped oil–gas cyclone separators. Their results indicated that the diameter and height of central channel has an insignificant effect on the flow field in the separator chamber. They also analysed the effects of decreasing and increasing the central channel diameter and height on pressure drop and tangential velocity (Gao et al., 2014). Elsayed (2015) predicted the complex non-linear relationships between pressure drop and geometrical dimensions based on Co-Kriging model. He used CFD simulations dataset and Muschelknautz method to develop his model. His new cyclone design was very close to the Stairmand high efficiency design and superior for low pressure drop (Elsayed, 2015).

Oh et al. (2015) predicted the internal flow field in a uniflow cyclone separator. Their results showed that the Eulerian-Lagrangian approach was adequate to simulate gas–solid mixture inside the cyclone. They concluded there were a recirculation zone under the vortex finder and a helical flow in the carrier gas outlet (Oh et al., 2015). Sgrott Jr. et al. (2015) used the Box COMPLEX optimization method combined with CFD simulation to find an optimal design of cyclones with a low particle loading (15 g/m^3) and small particle diameter (5 μm–15 μm). The collection efficiency of the optimized cyclone was 3.5 and 9.2% greater than those of the Stairmand and Lapple cyclones respectively. While for the pressure drop, the optimized design resulted in 6.3% lower than the Stairmand cyclone and 11.4% greater than the Lapple cyclone (Sgrott et al., 2015).

The measured particle concentration in the natural gas transmission and distribution network of the city of Kerman, Iran showed a high concentration of black powder in the network. It was found that the current filtration system cannot remove the solids properly. Having considered the size distribution of particles and evaluation of possible separation equipment of solid particles from natural gas flow, it was concluded that using cyclone separator before the filtration process in the City Gate Station (CGS) can highly increase the separation efficiency of solid particles (Azadi et al., 2012).

In this study, a high pressure cyclone was designed and simulated to separate black powder particles from natural gas for the inlet gas station of Kerman city (CGS #1), Iran. Stairmand cyclone with high efficiency was selected due to particle size of black powder in the gas inlet station. To increase the efficiency, the length of vortex finder of this cyclone was optimized by using Genetic Algorithm (GA). In order to design the cyclone, an algorithm is written, which has three input variables (i.e. gas flow rate, pressure drop and cut diameter). After selecting the appropriate conditions,