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A multi-objective optimization model to enhance the comprehensive performance of underground gas drainage system

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ABSTRACT

The underground gas drainage system plays a vital role in the underground drilling drainage which is widely used in Chinese coal mines. However, the pure gas drainage flow, gas concentration and energy efficiency, which together represent the comprehensive performance of gas drainage system, are generally low due to the mismatching between the drainage system and drainage objects. The optimization of gas pipeline system has been extensively investigated, but fewer studies consider the diversity and temporal correlation of drainage object characteristics and the multi-objectives of drainage system.

In this paper, a multi-objective optimization model, which fully considers the above factors, is built to achieve the match between the drainage system and drainage objects. Furthermore, the gas flow and methane transport model is established to calculate the values of multi-objectives and constraints. A derivative-free algorithm, bound optimization by quadratic approximation (BOBYQA), is proposed to solve the optimization model. Finally, the optimization model is applied to a typical modern coal mine and verified through the comparisons with field monitoring data and a recognized empirical formula. The optimization results reveal that (1) the variation trends of the three objectives with decision variables are different from each other, which indicates the optimal decision variables should be determined by considering all three objectives; (2) the optimization model can appropriately allocate the negative pressure in view of the interrelationship and different characteristics of drainage objects; (3) the decision variables can be adjusted to fit the characteristics change of drainage objects with time.

1. Introduction

Gas drainage can not only eliminate gas disaster in coal mines, but also provide clean energy and reduce greenhouse gas emission (Karacan et al., 2011; Pillalamarry et al., 2011). The widely used gas drainage method in China is underground drilling drainage (Xia et al., 2014), in which the underground gas drainage system plays a significant role. From Fig. 1, the drainage system connects to various drainage objects such as cross-measure boreholes, in-seam boreholes and the tube buried in gob. The relationships between the drainage negative pressure and gas drainage performance (i.e. gas drainage flow and concentration) are different for disparate drainage objects (Pan et al., 2014). Besides, the gas drainage concentration declines with time due to the air-leakage around the borehole (Liu et al., 2014; Zhou et al., 2016). Because of the diversity and temporal correlation of drainage object characteristics, it is difficult for gas drainage system to consistently match each drainage object without optimization. The mismatching can lead to the improper negative pressure for the drainage object, which further causes the low comprehensive performance of gas drainage system, including low gas drainage concentration, small pure gas flow and low energy efficiency. For instance, exorbitant negative pressure may result in the low gas drainage concentration and energy efficiency, whereas the excessively low negative pressure may induce the small gas drainage flow. According to the statistics, the average underground gas drainage concentration is lower than 30%, and the average pre-drained rate of coal seam gas is less than 23% in China (Zhou et al., 2014a). The annual electricity consumption of gas drainage system in a medium-scale coal mine normally reaches ten million kilowatt hours. Therefore, improving the

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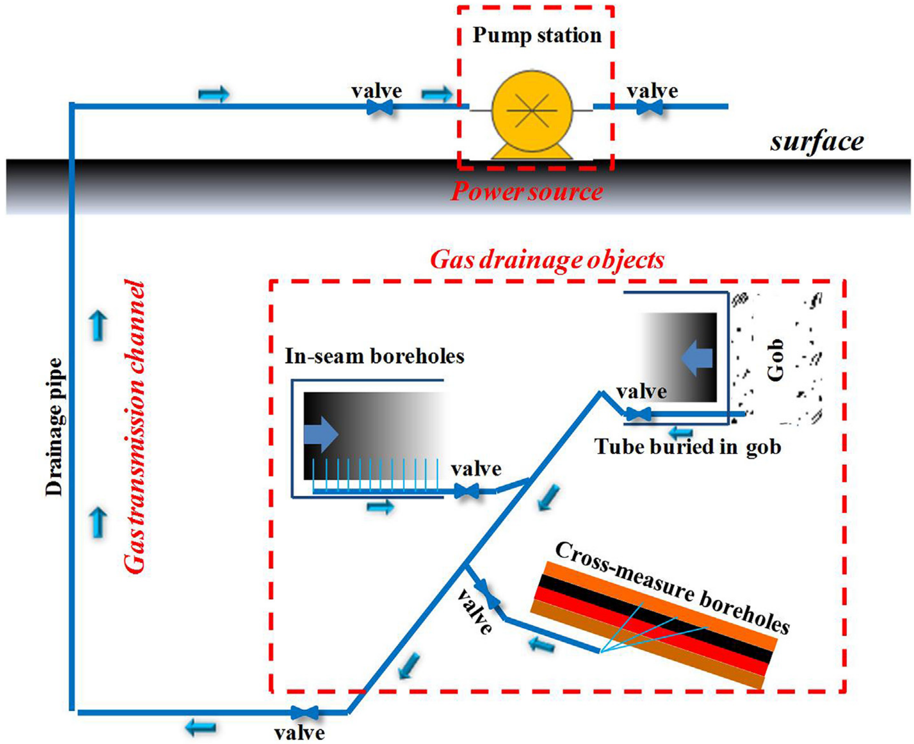

Fig. 1. The schematic diagram of gas drainage system.

comprehensive performance of gas drainage system, which can be achieved by optimizing the gas drainage system to match all different drainage objects, is of great significance.

The existing researches optimized the gas drainage system mainly by regulating the pipe diameters or valve opening degree. Zhai et al. (2008) and Ye et al. (2012) recognized the pipe sections with excessively large flow resistance using graph theory, and replaced the pipe sections with larger-diameter pipes for reducing the flow resistance. Liu et al. (2010) also proposed the optimum scheme of pipe diameter adjustment by using the mine ventilation simulation system to calculate the pipe resistance distribution. However, the adjustment of pipe diameters needs to replace the existing pipelines, which not only costs a lot in time and money but also disturbs the normal gas drainage and coal production. Unlike the above optimization, Wang et al. (2015) proposed to adjust the valve opening degree for improving gas drainage concentration of the in-seam borehole according to the correlation between negative pressure and gas drainage concentration. Nevertheless, the research only focused on the gas drainage concentration but neglected the total pure gas flow and energy efficiency which are also the important evaluation indicators of the drainage system. In addition, without considering the interrelationship among different drainage objects, the optimization research only concentrated on one drainage object. Therefore, the optimization was localized and its effect on the whole drainage system was not explicit.

The researches of underground gas drainage system optimization in coal mines are relatively scant, whereas the studies on the optimization of natural gas pipeline network are extensive, which can provide some reference for gas drainage system optimization. In these studies, some significant performance indexes such as transmission amount and operation cost are normally chosen as objective functions. Some key parameters of pipeline system such as the number of compressors and the compressor pressure are set as decision variables (Sun et al., 2000; Üster and Dilaveroglu, 2014; Chebouba, 2015). Diverse algorithms including particle swarm, ant colony, genetic algorithm and so on are used to solve the optimization problem (Wu et al., 2014; Zheng and Wu, 2012; Chebouba et al., 2009; Sanaye and Mahmoudimehr, 2013). However, there also exist differences between gas drainage system and natural gas pipeline system. Natural gas pipeline system connects to similar and stable gas sources which are not influenced by the operating condition of pipeline system. On the contrary, gas drainage system links diversified drainage objects whose gas flow and concentration are remarkably different from each other. The gas flow and concentration are also influenced by the negative pressure which is related to the operation condition of gas drainage system. Furthermore, the gas drainage concentration can decline with time. Therefore, the optimization of gas drainage system is more complicated than that of the natural gas pipeline in the above aspects.

In this paper, we build an optimization model for underground gas drainage system, which makes the drainage system consistently match each drainage object by fully considering the interrelationship and different characteristics of drainage objects, the characteristic change with time and the multi-objective. Pump rotate speed and valve resistance coefficients are chosen as the decision variables; total pure gas flow, gas drainage concentration and energy efficiency are set as the multi-objectives. Moreover, the gas flow and methane transport model is established to calculate the values of multi-objectives and constraints. A derivative-free algorithm, bound optimization by quadratic approximation (BOBYQA), is proposed to solve the optimization model. This optimization model is applied to a typical modern coal mine and verified through the comparisons with field monitoring data and a recognized empirical formula. This shows that this optimization model is an effective tool for improving the comprehensive performance of underground gas drainage system.