A Real-time Monitoring System for the Pipeline Network of Coalmine

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Abstract. The pipeline network of coalmine has the characteristics of widespread distribution and complex structure. It is difficult to detect abnormalities in time by manual when the faults occurred, which often lead to reduction in production. In this paper, a monitoring system is developed to monitor the operating conditions of the pipeline network in real-time. The system has abilities to dynamic monitoring, real-time display, and failure alarm and leakage location. Therefore, the faults detection and maintenance can be implemented timely to ensure the safety of coalmine production due to the real-time condition monitoring of the pipeline network. Moreover, the resources allocation, production efficiency and management level can also be improved obviously. In addition, this real-time monitoring system has shown significant performance in applying it in Dongtan Coal Mine, Yanzhou Coal Mining Co., Ltd and Wennan Coal Mine, Shandong Energy Xinwen Mining Group Co., Ltd, China.

Keywords: leakage location; monitoring system; coal mine; pipeline

1. Introduction

There are a large number of pipelines being used in petroleum, chemical, coalmine industry, and urban water supply and heating companies. When the leakage of pipeline occurs, it not only affects the normal production activities, results in economic losses, and may also cause environmental pollution or even lead to a fire and explosion.

The monitoring technique of pipeline has been developed since the 1970s [1-3] and a number of products have been launched since the 1980s. Instrotech Company in South Africa developed the Inspectafit boiler pipeline leakage monitoring system based on sound spectrum analysis technique. DETEX Company in the United States has developed the Series 2000 long pipeline leakage monitoring system [4]. Especially the WaveAlert system developed by the acoustic systems incorporated (ASI) company, has been used in gas, liquid, multiphase fluid and other application areas in the world [5].

The corresponding research works were firstly performed in the oil pipeline leakage detection in China. Many institutes have done a lot of works and made some progresses [6-12], such as Tianjin, Tsinghua, and Petroleum University, Zhongyuan, Daqing and Liaohu Oilfield.

Underground water supply system is an important and indispensable component in the coalmine, and plays a very important role in the maintenance of coalmine safe production. The pipeline network of the water supply system has the characteristics of widespread distribution and complex structure. However, in the coalmine of China at present, the normal way to check the pipeline network is the
manual inspection method, which has a lot of drawbacks: a) cost a lot of manpower and material resources; b) cannot monitor the global working conditions of system, and it is difficult to detect the sudden leakage event in time.

To minimize the impact on the mining production due to the water pressure abnormalities, a real-time pipeline monitoring system was developed according to the actual situation of China's coal mines. In this paper, the related work will be introduced briefly.

2. Hardware design

2.1 Overall structure of the system

Figure 1 shows the overall structure of the designed system. There are four parts as shown in the schematic which are (a) host computer located on the ground; (b) monitoring substations located in the underground; (c) sensors such as pressure or flow sensors, or actuators such as electric valves; (d) industrial Ethernet.

According to the layout situations of the pipelines underground coalmine, the pressure sensors, flow sensors, and electric valves are installed at the selected points in pipeline network. The monitoring substations are responsible for collecting the data of pressure and flow, and then processing, uploading them to the host computer via industrial Ethernet. At the same time, the substations can also send signals to control the opening or closing operation of the electric valve.

The host computer collects the pressure or flow data from the substations via Ethernet, and carries out the data storing, processing, querying, display and printing. Meanwhile, the control information of the operator can also be sent to the corresponding substations via Ethernet, and then the substation sends the control signal to the corresponding actuator. Moreover, the authorized users can access the host computer remotely, getting the monitoring information simultaneously.

![Figure 1](image_url)  
**Figure 1.** Overall structure of the system.

2.2 Substation scheme

Substation is designed by Siemens S7-300 series PLC as shown in figure 2, which consists of CPU (model 313C with 24 digital input channels, 16 digital output channels, 5 analog input channels and 2 analog output channels), power supply module PS 307, analog input module SM 332(with 8 analog input channels), Ethernet communication module CP 343-1 etc., and module FM 355 C for the closed-loop control occasion. Data acquisition is performed by the SM 332 module and the CPU together, and each substation provides a total of 13 analog signal input channels.
3. Software design of Host computer
The architecture of the software of the host computer is shown in figure 3, including data acquisition, fault diagnosis, database management, user management, information display and help modules.

Data acquisition module collects the current monitoring data of the sensors from the substation via Ethernet, and stores the data in the buffer. Fault diagnosis module performs the analysis of the current monitoring data, gives alarm information to the staff when an exception occurs. The leakage location module is used to calculate the position of the leakage point. Database management module stores the monitoring data to disk, and performs the historical data query, data report generation and printing. The user management module is used to set and modify the system password, add or delete users at different operating authority. Information display module displays the current monitoring data and alarm information real-timely, allowing authorized users view the information remotely.

The software of the host computer is developed by KingView, but the leakage location module is designed using Matlab. The data exchange operation between them is performed via DDE.

4. The method for leakage localization section
Negative pressure wave is generated when the pipeline leakage occurs. It travels upstream and downstream from the leakage and transmits to the terminals of the pipeline. The signals of the negative pressure wave are collected by the pressure sensors mounted on both the ends of the pipeline respectively, and the time difference between the two signals is calculated. According to the negative pressure wave propagation velocity in the pipe and the time difference, the location of the leakage point can be obtained.
Figure 4. The location principle of the leakage point.

The location principle of the leakage point is shown in figure 4. Where F1, P1 are the sensors of flow and pressure at the upstream end of the pipe, respectively, and F2, P2 are the corresponding sensors at the downstream end. L is the distance between the upstream and downstream sensors, X is the distance between the upstream and leakage point. \( V_o \) is the speed of water fluid, and \( v \) is the speed of the negative pressure wave in stationary water pipe.

Defining \( t_1, t_2 \) as the arrival times of the negative pressure wave at the upstream and downstream sensors, respectively. Let \( \Delta t = t_1 - t_2 \), then the following formula is expressed as

\[
\Delta t = \frac{X}{v - V} - \frac{L - X}{v + V}
\]

Due to \( v \) is much larger than \( V_o \), the equation (1) is simplified as

\[
X = \frac{1}{2} (L + v \cdot \Delta t)
\]

5. Key problems

5.1 Interferences and cancelling

However, for the practical pipeline system of coalmine, some normal pipeline operations such as the valve switched on or off may generate the negative pressure wave. In order to decrease misdiagnosis rate, it’s necessary to confirm if the leakage does occur. According to the mass balance principle, the data \( Q_1(t) \) obtained from the upstream flow sensor should be equal to the \( Q_2(t) \) collected from the downstream flow sensor when no leakage happened along the pipeline. If \( Q_1(t) \) is less than \( Q_2(t) \), which indicates that the pipeline leakage may happen.

5.2 Time difference \( \Delta t \) calculation

Cross-correlation method is used to calculate the time difference \( \Delta t \). The mathematical model can be expressed in equation (3)

\[
\begin{align*}
x_1(t) &= s(t) + n_1(t) \\
x_2(t) &= \alpha s(t + \Delta t) + n_2(t)
\end{align*}
\]

Where \( x_1(t) \) and \( x_2(t) \) are the signals detected by upstream and downstream pressure sensors, including the negative pressure wave signal \( s(t) \), and the measuring noise \( n_1(t) \) and \( n_2(t) \). \( \alpha \) is the coefficient related to the energy loss of negative pressure wave travelling along the pipeline.

To get the time difference \( \Delta t \), the cross-correlation functions of \( x_1(t) \) and \( x_2(t) \) are calculated according to the equation (4) and (5).

\[
R_{x_1x_2} (\tau) = E(x_1(t)x_2(t + \tau))
\]

Assuming that \( n_1(t) \) and \( n_2(t) \) are uncorrelated, then

\[
R_{x_1x_2} (\tau) = \alpha R_{ss} (\tau + \Delta t)
\]
Where, $R_{ss}(\tau + \Delta t)$ is the autocorrelation function of the negative pressure signal. The maximum value of $R_{x_1x_2}(\tau)$ can be extracted at $\tau = -\Delta t$ due to $R_{x_1x_2}(\tau + \Delta t) \leq R_{x_1x_2}(0)$. Therefore, the time difference $\Delta t$ can be obtained by the following steps: (a) calculate $R_{x_1x_2}(\tau)$ according to $x_1(t)$ and $x_2(t)$; (b) finds the maximum value of $R_{x_1x_2}(\tau)$ and the corresponding value of $\tau$, i.e. $\tau_m$; (c) finally, get the time difference $\Delta t = -\tau_m$.

5.3 The velocity of the negative pressure wave calculation
The speed of negative pressure wave in pipeline can be calculated according to equation (6):

$$v = \left( \frac{K/\rho}{1+(K/E)(D/e)C_1} \right)^{1/2}$$

(6)

Where $v$ denotes the speed of the negative pressure wave, m/s; $\rho$ is the density of water, $Kg/m^3$; $K$ is the elastic modulus of water, Pa; $D$ is the diameter of pipeline, m; $e$ is the thickness of pipeline, m; $E$ is the elastic modulus of the pipe material, Pa; $C_1$ is correction coefficient about constraints of pipeline.

6. Conclusion
The monitoring system of pipeline presented in this paper is a three-level distributed control system including host computer, substations designed by Siemens S7-300 series PLC, pressure sensors, flow sensors or actuators. It's able to monitor the operation state of the pipeline system of the coalmine, display real-time data, detect the faults, and perform leakage localization, providing an important meaning to the safety of coalmine production. Moreover, the resources allocation, production efficiency and management level can also be improved obviously. This real-time monitoring system has shown significant performance on applying it in Dongtan Coal Mine, Yanzhou Coal Mining Co., Ltd and Wennan Coal Mine, Shandong Energy Xinwen Mining Group Co., Ltd, China.

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