Small-scale area survey and analysis of Xinjiang's coal field fire in China

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Abstract: In this paper, Xinjiang's coal field is selected as the investigation area. Through a series of field surveys in Xinjiang, we made the small-scale area analysis of coal field fire using the ground remote sensing technique, and presented the reasonable evaluation of thermal anomaly conditions of Xinjiang's coal field arising from coal self-ignition fires. The results show that the method of small-scale area analysis is available for examining the extinguished actuality of coal fires and detecting fire spots. Therefore, for the selected fire-extinguished coal field in Xinjiang, the fire extinguishing effect was effectively analyzed by the means, and the new hidden thermal dangers were sought and diagnosed. For the coal field where the fire has not been extinguished, the utilization of this means approximately identified the severity and range of the fire area, and provided the quantitative and ground references for extinguish engineering.

Key words: coal field fire; thermal anomaly; remote sensing; small-scale

1 Introduction

China is the biggest coal producer in the world. However, coal field self-ignition fires have been one of severe natural disasters, which cause the tremendous loss of non-reproducible energy resources, massive destructions of land resources and a series of ecological environment pollutions. Therefore, Chinese government has placed the management of self-ignition fire disasters of coal fields on "21st Century China Agenda". It's necessary to carry out the practical investigations for coal field fire with the combinative means of field surveys and scientific analyses, detect the actual distributions of extinguished fires, old fires and newly developed fires, predict the evolvement trend, and quantitatively evaluate the explicit and potential effects of coal field fires on multi-scale ecological environments and climates. Therefore, the investigations not only offer effective ground references for extinguishment engineering, but also provide a new view for the research of area climate change and ecological response system which is of benefit to environmental protection[1].

Coal layer self-ignition process changes the geographical characteristics of coal fields. These changes include the magnetic field, electric field, microwave field, thermal field and spectral surface characteristics of self-ignition coal layer. According to the special geographical characteristics presented in coal fields affected by self-ignition fires, some kinds of detection methods and techniques for coal field fires have been developed, including the ground survey (for example, excitation potentiometry, magnetism method, radon measurement method, eudiometry) and the remote sensing technique. However, the development of remote sensing technique offers a powerful tool to detect the thermal anomalies of coal field fires in large regions. In recent years, some researcher carried out dynamic inspections and investigations on coal field fires basing on the remote sensing technique, and acquired prominent fruits in theory and applications which the management and control of coal field fires benefit from[2-8].

In China, the application of remote sensing technique to coal field fire study and investigation started from 1980s. It shows unexampled advantages in determining the thermal anomaly areas and the burnt rocks areas induced by coal field fires. In 1991, Aerial Photogrammetry and Remote Sensing Bureau carried through the primary remote investigations utilizing TM images of the coal fields in North of China. In 1992, Aerial Photogrammetry and Remote Sensing Bureau carried through the remote investigations for coal field fire adopting the aerial color and infrared scanning ima-

Received 23 *November* 2007

ging to analyze self-ignition characteristics of coal fields in Northwest China. In 1993, Aerial Photogrammetry and Remote Sensing Bureau did the systemic researches for coal fields in Xinjiang Autonomous Region. In 1994, Cooperating with European Communities, Chinese government continued to carry through the remote sensing for coal field fires. Aerial Photogrammetry and Remote Sensing Bureau and Internal Geoscience Academy of Holland engaged together in this program. Experts finished large-scale investigations of coal field fires utilizing integrating satellite remote sensing, aerial remote sensing and GIS technique.

Coal fields in China mainly lie in North China, Northwest China and Northeast China. Especially, Xinjiang in Northwest China possesses the most amounts of coal fields. Recently, coal field fires of Xinjiang became the main management aspect. The coal fire administration and programming engineering has successively implemented this work three times in 1981, 1997 and 2004, which effectively instructed extinguishment engineering and produced favorable effects through remote sensing and field surveys for coal field fire. In order to further assess the actuality of coal field, within this study, we chose the representative Zhunnan coal field of Xinjiang as the investigation area to make the corresponding analyses and evaluations for coal field fires through field surveys in 2005. The contents of this paper are organized as follows. Firstly, we introduce the actual distributions of Xinjiang's coal fields. Secondly, small-scale area analysis based on the thermal radiation information of coal field fire is introduced. Thirdly, the results and discussions are detailedly described. Finally, we present our conclusions.

2 The distribution of Xinjiang's coal fields

Xinjiang is the largest province and autonomous region in China. Xinjiang's topography is a mix of mountains, basins, deserts, oases, and rivers. Its climate is dry and continental, with warm summer and long, cold winter. The coal resource reserves are very abundant with about 1.8 Gt which is approximately 40.6 % of Chinese predicted reserves. The geological construction is simple and coal measure is diversified. Typical climate, natural environment, geological conditions and man-made factors bring about extensive self-igniting fires of coal fields spreading out over most areas of Xinjiang. The investigated Zhunnan coal field of Xinjiang locates in the Northern Tianshan Mountain Range, the Southern Zhungeer region with coal layers of Jurassic Badaowan and Xishanyao. It mainly includes weakly caking coal, gas coal and long flame coal. The self-igniting phenomenon is very bad in Zhunnan coal field, stretching from Wusu in the West to Jimusar in the East along the Northern Tianshan. Here, Liuhuanggou, Queergou, Shuixigou and Sangonghe sub-fields are selected as the primary coal fire investigation areas in Zhunnan coal field.

3 Small-scale area analysis based on the thermal radiation information

Based on the surface thermal anomaly information induced by coal field fires, the remote sensing may realize the dynamic detection through the thermal image analyses for multi-scale areas. For large-scale coal field fires, the thermal satellite images from different satellite sensors (for example, NOAA, Landsat, Bird, etc.) are used to analyze the characteristics of coal fires. Different satellite sensors have different spatial and spectral resolutions in the infrared electromagnetic spectrum channel which correspond to different detection capability. For middle-scale coal fire fields, the near surface thermal aerial scanning images are suitable to interpret coal fires. However, we chose the ground infrared remote sensing with more high spatial resolutions to detect small-scale thermal anomaly of coal fields.

3.1 Analysis principle[9]

Planck Law is the fundamental of radiation temperature measurements, which indicates the quantitative relationship between the radiation intensity and the temperature of ideal blackbody.

$$I_{b,\lambda}(T) = 2hc_0^2 / \left\{ \lambda^5 \left[\exp\left(\frac{hc_o}{\lambda kT} \right) - 1 \right] \right\} \quad (1)$$

Where, $k = 1.380\ 5 \times 10^{-23}$ J/K is the Boltzmann constant, $h = 6.625\ 9 \times 10^{-34}$ J·s is the Planck constant, $c_0 = 2.998 \times 10^8$ m/s is the velocity of light in vacuum.

Hence, the self-emission radiation intensity of actual surface may be expressed as

$$I_\lambda(T) = \varepsilon_\lambda \cdot I_{b,\lambda}(T) \quad (2)$$

Where, ε_λ is the spectrum directional emissivity of actual surface describing the deviation from ideal blackbody.

However, in measurements, the thermal radiation energy $E_\lambda^{i,j}$ reaching near-ground remote sensor includes not only the surface self-emission radiation, but also the environment reflection radiation, solar reflection radiation and atmosphere radiation,

$$E_\lambda{}^{i,j} = \varphi^{i,j} \cdot I_\lambda{}^{i,j} = \varphi^{i,j} \cdot [\tau_\lambda \varepsilon_\lambda{}^{i,j} I_{b,\lambda}{}^{i,j}(T_0{}^{i,j}) + \tau_\lambda (1 - \alpha_{e\lambda}{}^{i,j}) I_{b,\lambda}{}^{i,j}(T_e{}^{i,j}) + \tau_\lambda (1 - \alpha_{s\lambda}{}^{i,j}) I_{b,\lambda}{}^{i,j}(T_s{}^{i,j}) + \varepsilon_{a\lambda}{}^{i,j} I_{b,\lambda}{}^{i,j}(T_a{}^{i,j})] \quad (3)$$

Where, φ is the geometrical coefficient, T_0 is the thermophysical temperature of measured surface, T_e is the environment temperature, T_s is the solar radiation temperature, T_a is the atmospheric temperature, τ_λ is the atmospheric transmittance function, ε_λ is the spectrum emissivity of the measured surface, $\alpha_{e\lambda}$ is the surface spectrum absorptivity to environment radiation, $\alpha_{s\lambda}$ is the surface spectrum absorptivity to solar radiation, $\varepsilon_{a\lambda}$ is the spectrum emissivity of atmospheric radiation. Note that the subscript (i,j) represents the distribution coordinates of the measurement point in the remote sensor focal plane.

Through a series of measurement process, the output electrical signal $V^{i,j}$ of the remote sensor is

$$V^{i,j} = \gamma \cdot \Phi^{i,j} \int_{\lambda_a}^{\lambda_b} F(\lambda) \cdot I_\lambda^{i,j} \mathrm{d}\lambda \tag{4}$$

Where, $F(\lambda)$ is the spectrum sensitivity function of the remote sensor, (λ_a, λ_b) is the spectrum response range, γ is the photoelectric coefficient, Φ is the compositive non-spectrum variable (including geometry coefficient φ, pixel area of sensor, sub-pixel area of the measured surface).

Rewrite Eq. (4) as

$$\begin{aligned} V^{i,j} = {} & \gamma \cdot \Phi^{i,j} \int_{\lambda_a}^{\lambda_b} F(\lambda) \cdot \tau_\lambda \varepsilon_\lambda^{i,j} I_b^{i,j} \left[\lambda, T_0^{i,j} \right] \mathrm{d}\lambda + \\ & \gamma \cdot \Phi^{i,j} \int_{\lambda_a}^{\lambda_b} F(\lambda) \cdot \left[\tau_\lambda \left[1 - \alpha_{b,\lambda}^{i,j} \right] I_b^{i,j} \left[\lambda, T_e^{i,j} \right] + \right. \\ & \left. \tau_\lambda 1 - \alpha_{s,\lambda}^{i,j}) I_b^{i,j} (\lambda, T_s^{i,j}) + \varepsilon_{a,\lambda}^{i,j} I_b^{i,j} (\lambda, T_a^{i,j}) \right] \mathrm{d}\lambda = \\ & \gamma \cdot \Phi^{i,j} \int_{\lambda_a}^{\lambda_b} F(\lambda) \cdot \tau_\lambda \varepsilon_\lambda^{i,j} I_b^{i,j} (\lambda, T_0^{i,j}) \mathrm{d}\lambda + \\ & \psi (T_e, T_a, T_s, \alpha_{e\lambda}, \alpha_{s\lambda}, \varepsilon_{a\lambda}, \tau_\lambda) \end{aligned} \tag{5}$$

The main purpose of thermal radiation information analyses is to derive the distribution $(T_0, \varepsilon_\lambda)^{i,j}$ of the surface from the measured electrical signal $V^{i,j}$, that is, the temperature field $T_0^{i,j}$ and the emissivity field $\varepsilon_\lambda^{i,j}$ reflect the surface radiation information distribution of the surface. Therefore, the thermal anomaly and surface properties may be respectively distinguished from $T_0^{i,j}$ and $\varepsilon_\lambda^{i,j}$.

3.2 Analysis instrument

The heat energy of the burnt underground coal bed is upward released through rock heat conduction and air convection in cranny, which forms the coal field surface thermal anomaly. Due to the imbed depth and different heat released formats of coal fires, the coal field surface has different radiation temperatures. The surface temperature range is about 10 ~ 500 ℃. So the spectrum channel of the remote sensor is restricted to middle-far infrared spectrum. ThermaCAM™ P30, a kind of uncooled infrared camera, is the suitable equipment which realizes the non-contact measurements and analyses. P30 camera is with single-channel remote sensor, and has four inbuilt blackbody sources to rectify real time measurement results. Its main technical specifications are shown in Table 1.

Table1 Technical specifications of ThermaCAM™ P30

Detector type	Spectral range	Thermal sensitivity	Spatial resolution	Field of view/min. focus	Image frequency
Focal plane array (FPA), uncooled microbolometer 320 pixels × 240 pixels	7.5 ~ 13 μm	< 0.08 ℃ (at 30 ℃)	1.3 mrad	24° × 18° / 0.3 m (with 35 mm lens)	50/60 Hz non-interlaced

According to Eq. (5), even if the environment parameters $(T_u, T_a, T_s, \alpha_{e\lambda}, \alpha_{s\lambda}, \varepsilon_{a\lambda}, \tau_\lambda)$ and the detection distance are known, single-channel measurement is still unable to realize inverse calculations $(T_0, \varepsilon_\lambda)^{i,j}$ depending upon $V^{i,j}$. Usually the assumption of the approximate emissivity distribution $\varepsilon_\lambda^{i,j}$ needs to be made. Then the temperature field $T_0^{i,j}$ may be obtained. Under the circumstance of not requiring high accurate temperature measurement, this way could satisfy most of the requirements.

3.3 Analysis area

Liuhuanggou coal fire area in Changji, Queergou coal fire area in Hutubi County, Shuixigou coal fire area in Jimusar and Sangonghe coal fire area in Fukang were taken as the investigation areas. The main geographic and environmental parameters of the measured areas are shown in Table 2.

Table 2 Main geographic and environmental parameters

Figure	Geography coordinates (WGS 1984)	The approximate distance from the measured object/m	Environment temperature T_e/℃	Humidity	Atmosphere temperature T_a/℃	Emissivity (7.5 ~ 13 μm)
2-a	Northern latitudes: 43°43′00″, Eastern longitudes: 87°13′33″, Height: 1 129.949 m	10 ~ 100	25.7	30 %	13	0.85
2-b	Northern latitudes: 43°42′52″, Eastern longitudes: 87°13′31″, Height: 1 135.610 m	20	24.5	30 %	13	0.85

cont.

Figure	Geography coordinates (WGS 1984)	The approximate distance from the measured object/m	Environment temperature T_e/℃	Humidity	Atmosphere temperature T_a/℃	Emissivity (7.5 ~ 13 μm)
3-a	Northern latitudes: 43°47′47″, Eastern longitudes: 86°19′37.38″, Height: 1 812.7 48 m	100	22.8	37 %	13	0.85
3-b	Northern latitudes: 43°47′56″, Eastern longitudes: 86°19′42″, Height: 1 850.130 m	5	22.8	37 %	13	0.85
4-a	Northern latitudes: 43°55′59″, Eastern longitudes: 88°56′11″, Height: 1 085.801 m	30	23.8	37 %	13	0.85
4-b	Northern latitudes: 43°55′60″, Eastern longitudes: 88°56′08″, Height: 1 085.534 m	5	23.8	37 %	13	0.85
5-a	Northern latitudes: 44°03′59″, Eastern longitudes: 88°05′48″, Height: 996.208 m	200	15.2	37 %	13	0.85
5-b	Northern latitudes: 44°04′00″, Eastern longitudes: 88°05′47″, Height: 978.448 m	2	15.2	37 %	13	0.85

Note: 1) "The approximate distance from the measured object" is the round value, and the value deviation imposes no obvious effect on the results.

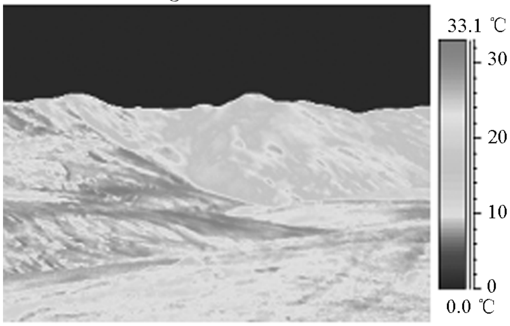
2) The atmosphere temperature is an estimated value, and the deviation imposes no obvious effect on the results.

3) The emissivity values of objects vary with different feature attribute, temperature, measuring waveband and viewing angle. In the above-mentioned measurement areas, the measurement images include normal rock and soil, burnt rock, vegetation, atmosphere, etc. At present, the accurate emissivity field could not be learned through simple experiments. Therefore, based on the technical manuals, we chose the emissivity values (0.85), which is approximately suitable for the objects such as rock and soil, to indicate the emissivity field of the imaging area. This value differs with the actual value, but it will not have an essential effect on the analysis of abnormal trend of thermal information field and temperature field.

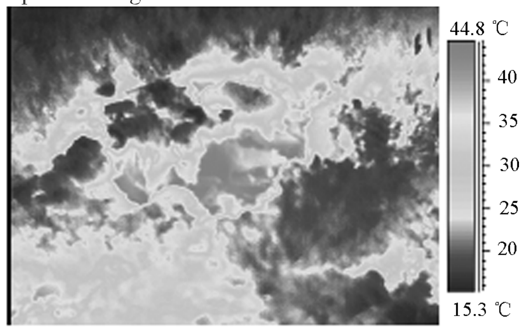
4 Results and discussions

The on-the-spot actual measurement results are shown in Fig. 1 to Fig. 4. The coal fires in Liuhuanggou coal field in Changji had been extinguished in 2004. We conducted an on-the-spot survey of fire area 4#. The layout of local temperature field of this area is shown in Fig. 1(a). The area had been a burning fire area before 2000, and the fire in the original burning area had been extinguished after three yeas of hard work of Xinjiang Fire Extinguishment Engineering Agent. The on-the-spot actual measurements indicate the highest temperature is 33.1 ℃ and the lowest temperature is 0 ℃. The rock and soil was solarized by the sun and the temperature rose with the absorption of heat, resulting in the highest temperature of the area higher than the temperature of the environment. The lowest temperature reflected the atmosphere temperature. Due to the fact that the infrared thermography with the waveband of 7.5 ~ 13 μm is not appropriate for accurate measurement of atmosphere temperature, the atmosphere temperature reflected by the lowest temperature had only served as a reference (it is the same case to the below-mentioned measurements). The analyses showed that there were no remarkable thermal abnormal spots, which means the fire extinguishing work was successful and met fire extinguishing standard for coal fire area. However, on the hillside (the detailed geographic coordinates shown in Table 2) to the north of fire area, there was a thermal abnormal area of less than 1 m^2. The layout of local temperature of this area is shown in Fig. 1(b). The highest temperature was 44.9 ℃ which was higher than the normal temperature. Rocks, soil and vegetation mingled in this area, and it was slightly damp and hot in nearing areas which were considered through initial analysis as a new hidden danger caused by the extinguishing blocking to the old fire area. At the same time, Urumchi County Coalmining was conducting productions in the range of this fire area, which could have probably damaged the formed fire extinguishing effect. Therefore, the fire area should be monitored to prevent the formation of new fire spots in the neighboring areas.

There were some sporadic thermal abnormal areas in Queergou in Hutubi County. This fire area covered the east and west hillsides of Daxigou Coalmine, whose main transport tunnels are located at the bottom of the Queergou fire area. The production of the coalmine and the natural collapse of the hillsides to its both sides had induced the formation of fire area in coal field. As shown in Fig. 2(a), the temperature of two narrow and long areas reached 100 ℃, and the area was about 1 ~ 2 m^2 with slight collapse on earth surface and no plants covering. Another thermal abnormal area viewed and measured from short distance was shown in Fig. 2(b). The area was about 1 ~ 2 m^2 with the temperature of 130 ℃. The rock stratum was baked by high temperature and turned into light-yellow burnt rock with loose soil in surrounding area. The fire area in Queergou was not big, and it was not easily identified by conventional large-scale remote sensing detection. But it should be paid enough attention.

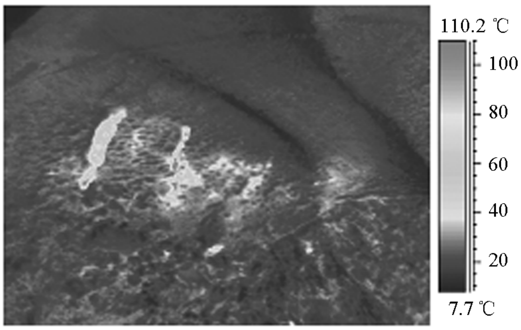


(a) Extinguished coal fire area

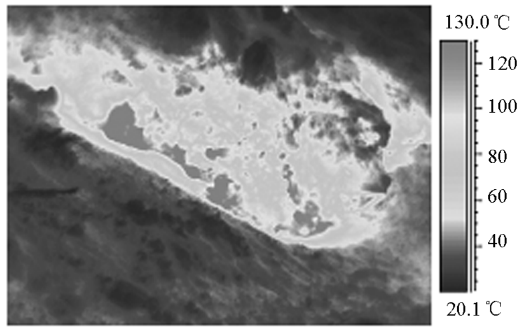


(b) Newly developed coal fire area

Fig. 1 Liuhuanggou coal fire area 4# in Changji

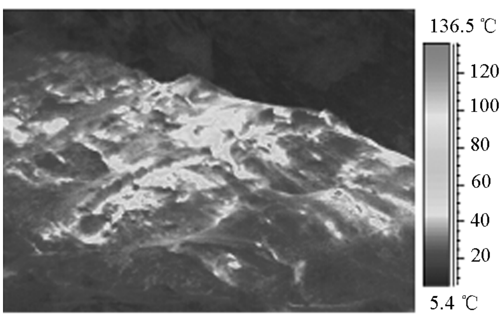


(a) West side of Queergou

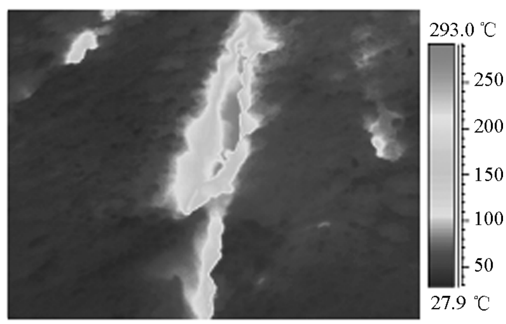


(b) East side of Queergou

Fig. 2 Queergou coal fire area in Hutubi County



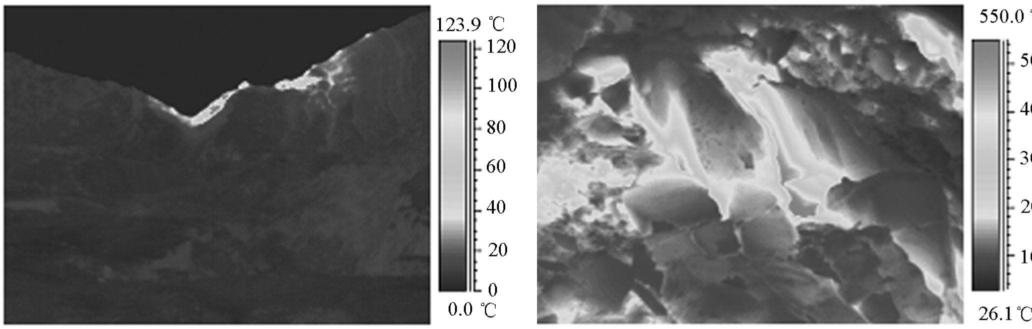
(a) Long-distance view



(b) Near-distance view

(c) Collapsed area

Fig. 3 Shuixigou coal fire area in Jimusar



(a) Long-distance view (b) Near-distance view

Fig. 4 Sangonghe coal fire area in Fukang

The condition of coal field fire area of Shuixigou in Jimusar was severe. Around this fire area was pasture land, and there were no mining activities nearby. The fire area was formed naturally. The area temperature field layout is shown in Fig. 3 (a). The thermal abnormal area range was wide with the area of dozens square meters. Hot flue gas could be seen from far away with smell of sulfur diffusing in the air, but the thermal abnormal area was sporadic and the surrounding areas were highly wavy mountainous land. Therefore it was not easily identified by conventional large-scale remote sensing detection, such as satellite. In the on-the-spot survey, a certain number of surface fissures of 10 cm wide were found on the north side of the mountain. As shown in Fig. 3(b), the temperature at the fissure opening was up to 293 ℃, hot flue gas was remarkably seen at the fissure opening, and there were burnt rocks near the fissure. There was an evident collapse in this fire area and the fissure was 7 km long from east to west and 2 ~ 3 m wide from south to north. The temperature of local area where burnt rocks are main body ranged from 50 ℃ to 200 ℃. Geological activities were evident in this area and the depth of the deep collapsed areas ranged from 2 m to 6 m, shown in Fig. 3(c).

The Fig. 4 (a) indicates the local thermal measurement chart of our survey of fire area in Sangonghe coal fire area in Fukang. There was an evident thermal abnormal area at the central part of the mountain and it took the shape of a strip of 5 ~ 10 m long with the highest temperature of 123 ℃. The temperature field layout of another thermal abnormal area in the coal fire area was shown in Fig. 4 (b). The area was 0.5 ~ 1 m^2. The highest temperature at the fissure opening is up to 550 ℃, and the temperature range of surrounding burnt rock is within 100 ~ 400 ℃. There was large-scale collapse in surrounding areas with pungent smell of sulfur in the air and strong scorching feeling. There were mining activities around the fire area, and meantime there had been some new collapse areas between the fire area and the mining pits, as shown in Fig. 5. These new collapse areas will soon become new coal fire areas. At present, the fire area is developing fast and this fire area should be the emphasis of the coming planning and controlling.

Fig. 5 New collapse areas in Sangonghe coalfield

5 Conclusions

In order to conduct the scientific analysis and evaluation on the current status of fire areas in coal fields in Xinjiang, we did an on-the-spot survey at the representative Zhunnan coal field (Liuhuanggou fire area in Changji, Queergou fire area in Hutubi county, Shuoxigou fire area in Jimusar and Sangonghe fire area in Fukang) in Xinjiang, and analyzed the thermal radiation information of small-scale area in coal field using the ground remote sensing technique. The conclusions achieved are as follows.

1) The aerial remote sensing and space remote sensing can realize the general survey of large-scale and meddle-scale fire areas in coal field. The factors, such as the timing of remote sensing images and geometric corrections, should be taken into consideration to correctly interpret the fire spots. However, in the actual survey, the ground remote sensing plays a good

supporting role and helps realize the rapid on-the-spot interpretation of fire spots.

2) For the selected fire-extinguished coal field, the fire extinguishing effect was effectively analyzed by the means of analysis of thermal radiation information of small-scale area, and meantime the new hidden thermal dangers were sought and diagnosed. For the coal field where the fire has not been extinguished, the utilization of analysis of thermal radiation information of small-scale area approximately identified the severity and range of the fire area, providing the reference for the fire extinguishing work.

3) We conducted the survey and analysis on the current status of coal fire fields in Xinjiang, hoped to provide further scientific supports for the administration improvement of current status of fire areas of in coal fields, and also provide foundation for the follow-up research of climate and ecological environment system.

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Foundation item: Supported by the National Natural Science Foundation of China (Grant Nos. 50606033 and 50674079) and National High Technology Research and Development Program of China (Grant No. 2007AA04Z178)