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Fuqiang Yang, Dongyang Qiu. *Exploring coal spontaneous combustion by bibliometric analysis*. Pages 1-10.

Coal spontaneous combustion (CSC) is a serious problem and remains a global safety concern in coal industry. In this paper, bibliometric analysis of the worldwide scientific publications on CSC was conducted to understand the characteristics and research trends in the Science Citation Index Expanded (SCI-Expanded) database. CiteSpace was adopted to evaluate the relationship among different countries/territories, authors, and keywords. In total, 829 documents on CSC were indexed, covering 1752 authors, 197 journals, 53 countries, and 591 institutes between 1984 and 2018. The studies related to CSC have been growing from 3 in 1984 to 126 in 2018. China, Australia, and the USA lead scientific production on CSC research, while more international collaboration should be strengthened in future. Wang DM, Qin BT, and Deng J are the most active researchers in this field. Fuel, International Journal of Coal Geology, and Energy and Fuels are the major sources of CSC publications. In addition, China holds three academic entities among the national-wide top 10 active institutions, with China University of Mining and Technology as the most productive research institutes. According to the frequency of keywords, low temperature oxidation, kinetics, mechanism, model are the dominant topics in CSC research. Similarly, there are new research hotspots appearing in recent years, related to 3 phase foam, fire extinguishment, and foam preparation.

- **Keywords:** Coal spontaneous combustion; Bibliometric analysis; CiteSpace

Wei Liu, Yueping Qin, Congling Shi, Dandan Guo. *Dynamic evolution of spontaneous combustion of coal in longwall gobs during mining-stopped period*. Pages 11-21.

Mining-stopped period is a high-risk stage owing to spontaneous combustion of coal in longwall gobs, but there have been few studies in this regard. To address this issue, a multi-physical coupling transient model was developed to characterize the evolution of coal self-ignition in longwall gobs during mining-stopped period. The initial condition of the model had used the temperature distribution of the gob at the moment when coal mining ends. The boundary of the solid temperature field, which was exchanging heat with airflo7w across working face, was set as the convective heat transfer condition. These improvements ensured that the calculative model was more realistic. The hazards due to spontaneous heating during stoppage period that were associated with some extrinsic mining parameters had been clearly evaluated. The results show that the high-temperature zones in the stoppage period are still located on the windward side of the

gob, and the calculated spontaneous combustion period of the gob is consistent with the scenario on-site. Furthermore, the mining parameters can be optimized to effectively increase the time required for spontaneous combustion in the stoppage state by increasing the longwall advance rate or reducing the thickness of crushed coal in the coal mining process, and by further reducing the ventilation flux during the stoppage period. This work can provide suggestions on how to extend the spontaneous combustion period for safely dismantling and moving machines and equipment away from the working face.

- **Keywords:** Mine fires; Mining-stopped period; Spontaneous combustion; Longwall gobs

Renato Benintendi. ***Fluid curtains for hydrogen sulphide control in refinery operations*****. Pages 22-34.**

Risk management of hydrogen sulphide is a challenging task in refinery operations. Despite the availability of very accurate modelling techniques and the compliance with internationally shared risk limits in hydrogen sulphide release prevention, post-release mitigation of hydrogen sulphide often remains a critical scenario. Fluid curtains are a well-known technology, which has successfully been adopted to mitigate mainly releases of hydrogen fluoride and ammonia. For these substances, high absorption effectiveness in pure water has enabled the technology to be included among the most advantageous methodologies in toxic hazard mitigation. Unfortunately, hydrogen sulphide is not absorbable in pure water, so that the application of fluid curtains would entail specific conceptual, design and operational aspects, in order for this technology to meet the same level of effectiveness attained for other toxic gases, especially when hydrogen sulphide concentrations are significant. This specific application has been dealt with to a very limited extent in the literature and no applications are reported at industrial level. Based on the elaboration of chemiabsorption absorption experimental data provided by van Krevelen et al. (1948), and by Astarita and Gioia (1964), this paper analyses and specializes the application of Fthenakis' model to hydrogen sulphide absorption in carbonate solutions, investigating and implementimg in full detail the available experimental data of chemisorption and the related fluid-dynamic aspects. A case study shows the high effectiveness of the technique, provided that chemistry and fluid dynamic aspects are fully identified and addressed in the design.

- **Keywords:** Process safety; Hydrogen sulphide; Fluid curtains; Fthenakis model; Absorption with chemical reaction

A.M. Birk, R. Eyssette, F. Heymes. ***Early moments of BLEVE: From vessel opening to liquid flashing release*****. Pages 35-46.**

The boiling liquid expanding vapour explosion (BLEVE) is well known but not well understood. Some still argue about what comes first, the BLEVE or the vessel rupture. Some believe the BLEVE is triggered by some pressure transient inside the vessel and this causes a superheat limit explosion which causes the vessel to rupture. Others believe it is the vessel rupture by some weakening process that leads to the BLEVE. This paper will provide evidence that the latter description that is correct for most, if not all BLEVEs observed in practice. This paper describes small scale experiments of aluminum tubes that were weakened by machining a thinned wall area over a specified length. The tubes were filled to a desired level with liquid propane and then the propane was uniformly heated electrically until the tubes failed. The failure pressures ranged from 10 to 33bar. The tube was instrumented to capture failure characteristics (pressure, temperature) and consequences: blast overpressure and imaging of the propane cloud and shock around the vessel; ground force under it; transient pressure and imaging of the boiling process inside the vessel. The work was done to improve our understanding of the fluid – structure interactions during the fire heat induced failure of a pressure vessel holding a pressure liquefied gas. We were specifically interested in the near field hazards including

blast overpressure and ground force. This paper will focus on the early milliseconds of the process where the vessel begins to open and a shock wave is formed and moves out into the surroundings. The imaging reveals presence of a Mach shock at the exit of the vessel at the early stage of the opening. A chronology of the event also shows that the lead shock is generated early in the explosion process, and is long gone before the liquid starts boiling, arguing that vapour expansion is the main contributor to the first shock overpressure.

- **Keywords:** BLEVE; Boiling liquid expanding vapor explosion; Explosion; Overpressure; Experimental results; High speed imaging; Timeline analysis; Lead shock; Explosive phase change

Todd Zhen, Katherine A. Klise, Sean Cunningham, Edward Marszal, Carl D. Laird. *A mathematical programming approach for the optimal placement of flame detectors in petrochemical facilities*. Pages 47-58.

Flame detectors provide an important layer of protection for personnel in petrochemical plants, but effective placement can be challenging. A mixed-integer nonlinear programming formulation is proposed for optimal placement of flame detectors while considering non-uniform probabilities of detection failure. We show that this approach allows for the placement of fire detectors using a fixed sensor budget and outperforms models that do not account for imperfect detection. We develop a linear relaxation to the formulation and an efficient solution algorithm that achieves global optimality with reasonable computational effort. We integrate this problem formulation into the Python package, Chama, and demonstrate the effectiveness of this formulation on a small test case and on two real-world case studies using the fire and gas mapping software, Kenexis Effigy.

- **Keywords:** Optimization; Flame detection; Process safety

Akbar Rostamabadi, Mehdi Jahangiri, Esmaeil Zarei, Mojtaba Kamalinia, Sean Banaee, Mohammad Reza Samaei. *A Novel Fuzzy Bayesian Network-HFACS (FBN-HFACS) model for analyzing Human and Organization Factors (HOFs) in process accidents*. Pages 59-72.

Human and organizational factors (HOF) play a significant role in the accident occurrence in chemical process industries (CPI). Human Factors Analysis and Classification System (HFACS) is a comprehensive framework widely used for analyzing HOFs involved in accidents. HFACS, however, has been criticized due to limitations such as the lack of quantitative analysis and interdependencies consideration among causal factors, and reasoning under uncertain conditions. This paper presents a novel accident analysis model incorporating Bayesian network (BN) and fuzzy Best Worst Method (fuzzy-BWM) into the HFACS framework to overcome the mentioned limitations. In the proposed model, BN is used to promote the ability of HFACS in providing both quantitative assessment and consider conditional dependencies among causal factors, while fuzzy-BWM is applied to relax the difficulties related to uncertainties and insufficient data on human errors and organizational failures. Application of the model was tested for analysis of HOFs in a real accident. The results revealed the capability of the model to quantify the failures and to provide an HFACS framework characterized by a flexible and dynamic analytical capability. The model was also able to identify key safety measures for development of effective intervention strategies in order to prevent future similar accidents.

- **Keywords:** Human factors analysis and classification system; Bayesian network; Fuzzy best worst method; Chemical process industries

Mengxue Wan, Mingkai Qu, Wenyou Hu, Weidong Li, Chuanrong Zhang, Hang Cheng, Biao Huang. *Estimation of soil pH using PXRF spectrometry and Vis-NIR spectroscopy for rapid environmental risk assessment of soil heavy metals*. Pages 73-81.

Environmental risk of heavy metals (HMs) in soil is commonly assessed by the different risk screening values of HMs under different pH based on soil environmental quality standards. To explore and establish a reliable, rapid and cost-effective method for detailed soil environmental quality survey with high-density sampling in the large-scale area is of significance for theoretical and practical research. In present study, using data from Yunnan Province, China, rapid analysis of soil HMs were conducted via portable X-ray fluorescence (PXRF) spectrometry, and that of soil pH was estimated by applying PXRF and visible near-infrared reflectance (Vis-NIR) spectroscopy data to partial least-squares regression (PLSR) and support vector machine regression (SVMR). Then we compared soil HM contamination grades calculated by conventional laboratory analysis data with those of rapid analysis data. It was found that soil HMs (i.e., As, Pb, Cu, and Zn) were successfully estimated by PXRF with high coefficient of determination (R2) above 0.97 ($P < 0.001$). SVMR with fused sensor dataset (here PXRF and Vis-NIR) provided the best predictive model for soil pH estimation (R2 = 0.86; the ratio of performance to deviation (RPD) = 2.21; the ratio of performance to interquartile distance (RPIQ) = 3.09). The Kappa coefficient of the classification was 0.91, a very high-level consistency between the assessment of soil HM contamination grades calculated by rapid analysis data and that of conventional laboratory analysis data. Therefore, our study suggested a promising method to rapidly detect soil HM contamination under different pH intervals, which would considerably reduce the financial burden of detailed soil HM survey great sampling number in large-scale areas.

- **Keywords:** Soil pH; PXRF; Vis-NIR; Data fusion; Soil heavy metals; Environmental risk assessment

Ugyen Dorji, Ugyen M. Tenzin, Pema Dorji, Ugyen Wangchuk, Gem Tshering, Cheki Dorji, Hokyong Shon, Kwabena Biritwum Nyarko, Sherub Phuntsho. *Wastewater management in urban Bhutan: Assessing the current practices and challenges*. Pages 82-93.

This study reviews the current wastewater management practices and their challenges in urban Bhutan. The study data was collected from the local authorities of 35 classified towns, and the field survey was conducted for the two representative towns of Thimphu City and Khuruthang town. The study observed that only eight of the 35 classified towns (22.8%) have public sewerage systems, with an average coverage of 19.7% of Bhutan's total urban population, or 7.4% of Bhutan's entire population. The imported modular wastewater treatment technology was significantly more expensive than alternative options; however, approximately six towns have already adopted this technology, due to a lack of space for a much cheaper waste stabilisation ponds. Currently, over 80% of Bhutan's urban population depends on the on-site sanitation system for their domestic wastewater disposal; however, over 40% of these properties lacked a soak-pit system for the safe disposal of septic tank effluent. Therefore, this study indicates that urban settlements in Bhutan are potentially subjected to overflow of significant amount of hazardous septic tank effluents directly into the environment posing significant risk to public and the environment. A critical urban plot space analysis indicates that the current system of on-site sanitation is inadequate and unsuitable for the current urban settings. Since it is impractical for the government to provide public sewerage system to all the towns, a low-cost public sewerage system, or an alternative and improved on-site treatment system, needs to be explored and promoted to achieve long-term environmental objectives.

- **Keywords:** Bhutan; On-site sanitation; Septic tank; Soak pit; Wastewater management; Pollution

Parvin Berenjkar, Mohsen Saeedi, Qiuyan Yuan. *Assessment of heavy metal release from dredged materials for different disposal scenarios: Study of Anzali international wetland, Iran*. Pages 94-104.

In aquatic systems, heavy metals are accumulated in sediments that can release from loosely bound fractions during dredging and disposal operations. Five sediment samples were collected from the entry of the Pasikhan River to Anzali wetland, where dredging is carried out. The heavy metal distribution in sediments was determined using a sequential extraction procedure that showed Pb and Cd contribution mostly to non-residual phase (>80%). Heavy metal release from dredged materials was assessed for different disposal scenarios using pathway specific leaching tests. The highest release was attributed to Pb and Cd in open-water disposal (232 and 12.6μg/L, respectively), confined disposal facilities (CDF) (180 and 12.2μg/L, respectively), and landfilling (679 and 5.6μg/L, respectively). The metal bioavailability and bioaccessibility were assessed using single extraction methods for agricultural use and other disposal scenarios. The metal bioavailability was in the order of Cd ~ Pb>Cu>Mn>Zn>Fe>Ni>Cr. In case of open-water disposal, metal concentrations in water column were higher than water quality standards but lower than background amounts at the disposal site. In confined disposal, the concentrations in effluent and leachate of CDF occasionally exceeded the allowable limits. Finally, in case of landfilling, metal concentrations in leachate exceeded that of other methods, but remained below the USEPA recommended limits. According to implemented risk assessment indices, the risk level for heavy metal bioavailability and bioaccessibility was medium and very high, respectively, and Cr had carcinogenic and non-carcinogenic risk for human health.

- **Keywords:** Heavy metals; Bioavailability/bioaccessibility; Sediment disposal; Leaching test; Sequential extraction

Maria Cristina Collivignarelli, Marco Carnevale Miino, Marco Baldi, Sabrina Manzi, Alessandro Abbà, Giorgio Bertanza. *Removal of non-ionic and anionic surfactants from real laundry wastewater by means of a full-scale treatment system*. Pages 105-115.

Surfactants are considered emerging contaminants, that can represent a source of problems for environment and human health. This paper aims to quantify the effect of a thermophilic aerobic membrane reactor (TAMR), nanofiltration (NF) and adsorption on activated carbon (AC) for the removal of non-ionic surfactants (TAS) and anionic surfactants (MBAS) from a real laundry wastewater. This study included daily monitoring of a full-scale plant for more than three months. The results showed that the TAMR process has been able to withstand high stress conditions (sudden load peaks) and resist to a high concentration of surfactants, allowing it to perform an effective pre-treatment activity. Both in the case of the removal of TAS and of MBAS, the combination of processes made it possible to obtain higher removal yields. Evaluating the operating costs, the results suggested that TAMR+NF represented the optimal combination of processes for the removal of TAS and MBAS. The TAMR+NF+AC sequence allowed almost complete removal of TAS (> 95%) and high removal of MBAS (> 76%) but the costs per unit of mass removed were high.

- **Keywords:** Surfactants; Thermophilic; Biological; Nanofiltration; Activated carbon; Laundry wastewater

Mahsa Akbari, Peyvand Valeh-e-Sheyda. *CO2 equilibrium solubility in and physical properties for monoethanolamine glycinate at low pressures*. Pages 116-125.

In practical applications, water vapor always coexists with natural gas. As such, the concentration of the ionic liquids (ILs), as promising absorbents for carbon dioxide (CO2) removal, is a crucial parameter sensitively affecting CO2 solubility. In this work, a novel amino acid anion (Glycinate) based IL was synthesized, characterized, and applied for CO2 uptake. Preliminary physicochemical measurements at temperatures of 303–323K showed that increasing the IL purity has adverse effects on density, viscosity, and surface tension of the [MEA][GLY]. The impact of the presence of water in the IL samples was also investigated on the CO2 loadings over the temperature ranges of 303–323K and up to a pressure of 600kPa. Among the four aqueous solutions of the IL, the highest CO2 loading of 1.02 (mol CO2/mol IL) was achieved for aqueous IL of 25wt% at an equilibrium pressure of 1.35bar and a temperature of 303.15K. It is found that with increasing equilibrium pressure to about 6.2bar, the loading rate has reached 1.32 (mol CO2/mol IL), which is almost 2.64 times higher than that of the conventional primary amine (0.5mol CO2/mol IL). It is found that although the proposed IL is a promising absorbent for the capture of CO2, highly concentrated of the [MEA][GLY] is not the feasible concentration for CO2 uptake.

- **Keywords:** Absorption; Carbon dioxide; Equilibrium; Ionic liquid; Monoethanolamine glycinate

Qianqian Li, Zhiyu Yan, Yemiao Zhang, Liangchen Wang, Hu Liu, Zuohua Huang. *Experimental study on the explosion characteristics of methylcyclohexane/toluene-air mixtures with methanol addition at elevated temperatures*. Pages 126-133.

Explosion characteristics of methylcyclohexane (MCH)-methanol- and toluene-methanol-air mixtures were investigated in a closed vessel at 0.1MPa covering wide blending ratio range. The explosion hazard was evaluated by determining important explosion parameters. Comparisons were made between MCH- and toluene-air mixtures and the effects of methanol addition were identified. Results show that MCH-air yields approximate peak explosion pressure with toluene-air mixture but higher maximum rate of pressure rise. For the blend-air mixtures, the methanol addition exerts limited effect on the peak explosion pressure. For the maximum rate of pressure rise, the 20% methanol addition results in slight variation and further addition of methanol causes significant increase tendency. Regarding explosion phase parameters, toluene-air has longer explosion delay and burn period than MCH-air does. At the lean mixture side, the methanol addition generates slight decreases of explosion delay and burn period. At the rich mixture side, 20% methanol addition slightly extends the explosion delay and yields limited effect on the burn period. Further addition of methanol could significantly decrease the explosion delay and burn period simultaneously. Finally, the deflagration index was exponentially correlated with the explosion delay or burn period with the fitting constants listed.

- **Keywords:** Cyclic fuel; Methanol; Explosion pressure; Deflagration index; Explosion phase

Behzad Nazari, Mohammad Hossein Keshavarz, Amin Hassanzadeh. *Reliable prediction of the flash point of organic compounds containing hazardous peroxide functional groups as compared to the best available methods*. Pages 134-141.

This work introduces a simple method for reliable prediction of the flash point of various types of organic compounds containing hazardous peroxide functional groups that are significant for safety measures in industrial processes. Different types of 116 organic peroxides including hydroperoxides, dialkyl peroxides, α-oxygen substituted alkyl hydroperoxides, and dialkyl peroxides, primary and secondary ozonides, peroxy acids, diacyl peroxides (acyl and organosulfonyl peroxides), and alkyl peroxyesters (peroxycarboxylates, peroxysulfonates, and peroxyphosphates) are used to derive the new correlation. The new model is derived by considering three important different types of effective structural parameters, which contain the number of carbon and hydrogen atoms as well as the number of hydrogen bonding groups under certain conditions and the existence of some specific molecular fragments. Various types of statistical assessments are done to confirm the high reliability of the new model. Internal and external validations of the new model confirm that it is robust. High reliability of the new model is compared with outputs of the new software (TEST software) including a variety of Quantitative Structure-Activity Relationship (QSAR) methodologies, which are based on the methods of Food and Drug Administration (FDA), as well as one of the best structural group contribution (SGC) methods. The values of Mean Absolute Percent Error (MAPE) of the new model, TEST software and SGC are 5.18, 8.54 and 12.34, respectively.

- **Keywords:** Flash point; Organic peroxide; Molecular fragment; Safety

Yawei Song, Shengqiang Yang, Qin Xu, Jiawen Cai, Xincheng Hu, Naiwen Sang, Zhicheng Zhang. *Effect of low-temperature oxidation of coal with different metamorphic degrees on coal quality characteristics and outburst comprehensive index*. Pages 142-152.

Outburst prevention and control measures such as protective seam mining and coal seam gas pre-drainage can cause low-temperature oxidation of coal seam, and there is a lack of research on the changes in coal quality characteristics and outburst comprehensive index during low-temperature oxidation. In this paper, the changes of coal quality characteristic indexes during oxidation of coals with different metamorphic degrees, the initial gas emission velocity and the firmness coefficient were measured, the influence of coal quality characteristics on outburst comprehensive index is studied, and the change of outburst comprehensive index K=Δpf in the low-temperature oxidation process was analyzed. The results show that for coal with different metamorphic degrees, the coal with a lower metamorphic degree enters the stage of inherent moisture evaporation later and is more likely to undergo decomposition and volatilization of volatile matters. In the midterm of low-temperature oxidation (120–160°C), the growth rates of △p values and the decline rates of f values of coal samples with higher metamorphic degrees tend to decrease. It can be known that the K value of bituminous coal and anthracite are more than 25 during the whole oxidation heating stage, which shows a serious outburst risk. For these coals, effective outburst prevention measures must be taken to prevent outburst risk and inhibit coal spontaneous combustion. In contrast, for lignite coal, the growth rate of △p value and the decline rate of f value keep increasing in the midterm of low-temperature oxidation, due to the joint action of moisture evaporation and volatile decomposition and volatilization. The K value of Lignite is more than 15 when oxidation temperature rises to 150 °C, which shows a general outburst danger. According to the analysis results in the midterm, appropriate measures must be taken to inhibit coal oxidation when local or overall temperature of coal seam reaches 130 °C.

- **Keywords:** Metamorphic degree; low-Temperature oxidation; Coal quality characteristic index; Outburst comprehensive index

Jiahao Liu, Jinhui Wang, Mingyi Chen. *Estimating the trajectory length of buoyant turbulent jet flames issuing from a downward sloping nozzle*. Pages 153-159.

Downward sloping buoyant turbulent jet fires occur frequently during flammable gas leakage, while its flame trajectory, especially the quantitative length, is not well described. The flame trajectory lengths of downward jet fires with five sloping angles (0°, 15°, 30°, 45°, 60° relative to the horizontal) and two nozzle diameters (8 and 10mm) were experimentally investigated. A novel method to quantify the flame trajectory length is proposed based on the flame outlines, and the results obtained show good agreement with the existing data of horizontal jet fires. For cases with differently inclined angles, the normalized flame trajectory length as a function of nozzle diameter can be correlated with the Froude number Fr1/5 and dimensionless heat release rate Q*2/5, but not as function of the tilting angle as this is not considered in the existing correlations. In order to establish a global model for predicting the flame trajectory length of downward sloping jet fires as function of the tilting angle of the nozzle, a remodified Froude number (Frf*) is proposed, and the correlated result can describe all the current experimental results together with that of horizontal and vertically downward-oriented jet fires in the literature.

- **Keywords:** Jet fire; Downward sloping angle; Flame geometry; Flame trajectory length

Subhasish Majee, Gopinath Halder, Tamal Mandal. *Formulating nitrogen-phosphorous-potassium enriched organic manure from solid waste: A novel approach of waste valorization*. Pages 160-168.

This work investigates the feasibility of utilizing solid wastes viz. wet blue leather, poultry bone and water hyacinth for the production of N-P-K (Nitrogen-Phosphorous-Potassium) enriched organic fertilizers. The nitrogenous component was derived from wet blue leather after exhausting it of Chromium using bi-directional base hydrolysis followed by acid hydrolysis. Upon hydrolysis, a solid collagenic material with significant amount of nitrogen was obtained as a byproduct. Poultry bone was sterilized and then dried at 80°C before crushing to obtain bone meal. Water hyacinth was sun-dried before calcination at 450°C in a muffle furnace to obtain ash. In order to produce N-P-K rich formulation of organic manure, collagen was amalgamated with phosphorus laden poultry bone meal and potassium enriched water hyacinth ash. The efficacy of the resulting organic N-P-K based manure was examined as a nutrient source on Catharanthus roseus (Madagascar Periwinkle). Ammonia analysis for nitrogen content of fertilized soil demonstrated that free nitrogen content in the soil mixed with organic N-P-K formulation was 45.16% and 19.35% higher than natural soil and soil mixed with commercial fertilizer, respectively. Interactive DNA study of organic N-P-K formulation revealed a low intercalation and less interactivity with DNA in nature than commercial fertilizer. Fertilising Catharanthus roseus plant using organic N-P-K fertilizer resulted in significantly higher growth and flowering compared to that observed using commercial fertilizer. Hence the newly developed organic fertilizer could be an efficient and environmentally benign organic nutrient for successful application in the agriculture to enhance the plant growth, over chemical fertilizer.

- **Keywords:** Solid waste; Formulation; Organic fertilizer; Plant growth

Timothy G. Holloway, John B. Williams, Djamila Ouelhadj, Barry Cleasby. *Process stress in municipal wastewater treatment processes: A new model for monitoring resilience*. Pages 169-181.

Although not-well-understood, process stress could provide a novel approach to resilience analyses in wastewater treatment processes by identifying the influence of a stressor on wastewater processes. This paper identifies how industry and academia view the concept of process stress in wastewater treatment processes. It also investigates how individuals, their role and education influence their decision bias and their propensity to use decision support tools. Survey results from 255 respondents showed that many wastewater professionals still have a preference to use personal or company-specific spreadsheets (33%), with a similar proportion of respondents using simulation and decision support tools (29%). The concept of process stress in wastewater treatment was well understood by industry and academic professionals as a variance from benchmarked conditions. This analogy of process stress means that it can be either, a positive or negative magnitude of variation from a benchmarked state, which expands on the approach taken in current resilience and benchmark simulation models. Therefore, the concept of process stress was a well understood by a vast majority of respondents, with 82% of respondents agreeing that an analytical tool that considers process stress would be a useful contribution to developing the understanding and management of process resilience. The study also highlights the requirement for a process stress analysis methodology, which builds on current resilience methods and separates the stressor (cause) from process stress (effect). Overall, this research has identified the requirement to measure and analyse stresses in wastewater treatment processes and recommends a strategy to develop this methodology.

- **Keywords:** Resilience; Wastewater process stress analysis; Benchmark; Wastewater process analysis; EDSS; Process modelling

Zongqing Tang, Shengqiang Yang, Guang Xu, Mostafa Sharifzadeh. *Disaster-causing mechanism and risk area classification method for composite disasters of gas explosion and coal spontaneous combustion in deep coal mining with narrow coal pillars*. Pages 182-188.

In order to reduce the stress on the underlying coal seam and improve mining efficiency in deep coal mining activities, narrow coal pillars are often used. They are the main factor that increases the risk of coal spontaneous combustion in the goaf. Based on the on-site experiment and the experimental analysis in the laboratory, this paper adopted correlation coefficient criteria and safety principles to research the disaster-causing mechanism of such risk. It also classified and divided the studied area into different risk levels to effectively manage it. The results show the coal mass fractures generated by the movement of stress concentration points on the narrow coal pillars is the main factor that contribute to the increased spontaneous combustion in the goaf. The two main forms are gas explosion caused by CH4 flowing into the roadway and spontaneous combustion of residual coal caused by O2 flowing into the nearby goaf. By adopting correlation coefficient criteria and safety principles, this paper selected two indicators, gas-impermeability of narrow coal pillars and risk degree of residual coal spontaneous combustion in the goaf to divide the whole narrow coal pillars and goafs into three areas, namely "Safe Area", "General Area" and "Dangerous Area". This can maximize safety benefits with the lowest cost and guarantee safe and efficient coal mining.

- **Keywords:** Deep coal mining; Narrow coal pillar; Composite disaster; Disaster-causing mechanism; Area division

Pengfei Wang, Xuanhao Tan, Lianyang Zhang, Yongjun Li, Ronghua Liu. *Influence of particle diameter on the wettability of coal dust and the dust suppression efficiency via spraying*. Pages 189-199.

Spraying is a main technique means for the prevention and control of coal dust in coal mines. The dust suppression efficiency by spraying is highly correlated with the

wettability of coal dust. There are many influencing factors for the wettability of coal dust, among which the particle diameter of dust is one of the most significant factors. In order to analyze the influence of particle diameter on the wettability of coal dusts and the dust suppression efficiency via spraying, 18 different samples with 3 different types of coal samples and 6 different particle diameters were selected in this study. A series of experiments were designed and performed to evaluate the micro-properties, the wettability, and the dust suppression performance via spraying of coal dust. According to experimental results on the micro-properties, the amount of hydrophilic oxygen-containing functional groups gradually dropped with the decrease of the particle diameter. As the particle diameter decreased, the specific surface area of coal dust gradually increased while the average diameter of the internal pores decreased. Based on the experimental results on the wettability of coal dust, the wettability of the dust with the same property dropped with the decrease of particle diameter. Finally, based on the experimental results on the dust suppression efficiency via spraying, the dust suppression efficiency via spraying was determined by both the wettability of coal dusts and the value of $\triangle D50$ (the absolute value of the difference between the droplet diameter and the dust particle diameter). As the particle diameter of coal dust increased, the dust suppression efficiency via spraying first increased and then decreased.

- **Keywords:** Coal dust; Wettability; Micro-properties; Particle diameter; Spraying dust suppression

Martina Casciano, Nima Khakzad, Genserik Reniers, Valerio Cozzani. Ranking chemical industrial clusters with respect to safety and security using analytic network process. Pages 200-213.

The industrial clustering process in the chemical industry is becoming progressively more important due to economic, social and political issues. Industrial clustering means agglomeration of companies in the same geographical area in order to increase productivity and reduce costs. Nonetheless, clustering also has some important safety and security implications. The aim of this study is twofold: firstly, the development of an algorithm for the classification of chemical industrial clusters with regards to safety and security risks. Secondly, considering the importance of a multi-plant safety and security management system, highlighting the greater efficiency in the reduction of risk where adequate cooperation exists. The methodology is divided in three main steps, namely, "selection" (of the chemical parks to be processed), "assessment" of average hazard and vulnerability of installations within the cluster area, followed by an analysis of the relationships within companies in terms of strategic and operational cooperation, and "ranking". The last step evaluates the strong influences of the above-mentioned parameters through the analytic network process (ANP) and leads to a final classification.

- **Keywords:** Industrial cluster; Hazard; Vulnerability; Safety and security risks; ANP

Azra Nawar, Hosein Ghaedi, Majid Ali, Ming Zhao, Naseem Iqbal, Rashid Khan. *Recycling waste-derived marble powder for CO2 capture*. Pages 214-225.

One of the most promising technologies to reduce global emissions of CO2 as a major greenhouse gas is called calcium looping (CaL). Current calcium-oxide-based sorbents used in CaL process either expensive or lose their effectiveness over many cycles. On the other hand, the negative impact of large amounts of waste marble powder generated by cutting and polishing marble on the environment cannot be ignored. With the aim of cleaning up both carbon emissions and waste at the same time, therefore, this study will investigate the application of inexpensive waste marble powder as potential alternative to current commercial calcium-carbonate sorbents for capturing CO2. The marble powder-based sorbents were characterized by SEM-EDS, XRD, TGA, XRF and N2 sorption

analysis. To improve the CO2 capture performance, the waste marble powder was modified with several various acids. The results revealed that an increase in the acid volume has changed the CO2 uptake capacity and stability of sorbents particularly propionic acid (PA) and acetic acid (AA). It was found that the carbonation conversion of modified sorbents with AA-50% and MD PA-50 were 70.2% and 76%, respectively, higher than that of unmodified CaO sorbent after 20 cycles. In terms of CO2 uptake capacity, modified sorbent with PA-50% showed the highest performance of 0.675g CO2/g sorbent, while, modified sorbent with AA-50% showed improved cyclic stability over multiple cycles (average decay 1.24mg CO2/cycle) regarding the stability. Therefore, these results indicate that (acid-modified) CaO derived from marble powder is much better sorbent than limestone and can be used as a low cost and environment-friendly sorbent for CO2 capture.

- **Keywords:** Waste marble powder; Organic acids; CaO-based sorbent; CO2 capture; CaO conversion

Horng-Jang Liaw. *Deficiencies frequently encountered in the management of process safety information*. Pages 226-230.

Process Safety Information (PSI) provides the fundamental information necessary for developing the elements of Process Safety Management (PSM). We report the PSI management deficiencies found in PSM audits of more than 70 plants. It should be noted that the PSM audits were not limited to OSHA requirements. The deficiencies found were frequently encountered in the management of the PSI element. The chemical hazards information provided on the Safety Data Sheets (SDS) are not sufficient and may not be appropriate for the process condition used; therefore, the chemical hazards information should not be limited to only the SDS. Although the information provided by the SDS satisfies the OSHA requirements, it is suggested that management further develop the chemical hazards information necessary to ensure the safety of the process. Process incidents resulting from undesired reactions are more frequent than from the desired. Therefore, in terms of safety, the process chemistry of the undesired reactions is essential information for the process technology. However, such undesirable reactions are not identified, and their process chemistries are lacking for most processes. The frequently encountered problem for the information of the process equipment is the inconsistency between the piping and instrument diagram and the actual process. Summarily, the necessary information of the PSI should be developed based upon the characteristics of the process.

- **Keywords:** Process safety information; Process safety management; Chemical hazard; Process technology; Process equipment

Irina Morosanu, Carmen Teodosiu, Daniela Fighir, Carmen Paduraru. *Simultaneous biosorption of micropollutants from aqueous effluents by rapeseed waste*. Pages 231-239.

The simultaneous biosorption of a binary metal-dye mixture onto rapeseed waste (RS) resulted from oil press was investigated. Lead (Pb) and Reactive Blue 19 (Rb19) dye were used as model pollutants due to their low biodegradability and toxic effects, even at low concentrations. The biosorbent was minimally prepared before use and was characterized by using infrared spectroscopy before and after the simultaneous biosorption. The biosorption rates of each sorbate was determined using kinetic tests at three Pb:Rb19 molar ratios. The kinetic modelling revealed that the process is better described by a pseudo-second order rate of reaction. Freundlich isotherm model could explain the equilibrium data for the dye uptake, while Langmuir isotherm, followed by Freundlich model, could describe the biosorption of lead. Biosorption selectivity was determined at various initial concentrations of the pollutants in aqueous phase. At small to medium concentration ranges, the presence of Pb(II) ions determined an increase in

the uptake of Rb19, as compared to its individual biosorption. By applying Boyd's model, it was observed that film diffusion is the rate controlling step of the simultaneous biosorption process. Desorption was realized separately for each pollutant, as a function of the eluting pH. Through this approach, the waste biosorbent can be uploaded with two different type of micropollutants removed from wastewater, the sorbent being further reused or disposed in a controlled way, thus considering the circular economy principles. The practical implications of the simultaneous biosorption using RS waste were also discussed (reactor configuration, scale-up methodology and exhausted biosorbent management).

- **Keywords:** Simultaneous biosorption; Pb(II); Reactive blue 19; Wastewater; Desorption

Ravi Kumar Sonwani, Balendu Shekhar Giri, Ram Sharan Singh, Birendra Nath Rai. *Studies on optimization of naphthalene biodegradation using surface response methodology: Kinetic study and performance evaluation of a pilot scale integrated aerobic treatment plant*. Pages 240-248.

In the present work, the biodegradation of naphthalene (polycyclic aromatic hydrocarbon) has been studied using isolated Bacillus cereus RKS4 (MH681588.1). The process variables such as pH (5.0–9.0), temperature (25–40°C), and naphthalene concentration (10–50mg/L) have been optimized using central composite design (CCD) of response surface methodology (RSM). Analysis of variance (ANOVA) shows a high value of R2 (0.98) and confirm that the second-order regression model is in agreement with experimental data. The maximum removal of naphthalene (96.1%) were obtained at pH of 7.0, naphthalene concentration of 10mg/L, and temperature of 32.0°C. Further, the biodegradation of naphthalene was studied in a pilot-scale integrated aerobic treatment plant (IATP) at various flow rates. GC–MS analysis reveals that catechol and 2-naphthol were the major intermediate metabolites observed during biodegradation. The kinetics of naphthalene biodegradation was examined by Monod and Teissier-Edwards models and kinetic parameters were obtained to be μmax: 0.165 per day, KS: 7.91mg/L by Monod and μmax: 0.321 per day, KS: 11.5mg/L, Ki: 33.2mg/L by Teissier-Edwards.

- **Keywords:** Bacillus cereus RKS4; Naphthalene; Optimization; Biodegradation; Kinetic study

Monzure-Khoda Kazi, Fadwa Eljack, Saad Ali Al-Sobhi, Nikolaos Kazantzis, Vasiliki Kazantzi. *Application of i-SDT for safer flare management operation*. Pages 249-264.

Utilizing unburn flare streams in a safe way represents one of the key challenges during flare alternatives implementation. Most of the time, process safety is considered on a supplemental basis after accomplishing a detailed plant design and economic analysis. The prime reason is the lack of a systematic design tool that facilitates the incorporation of inherently safer design principles into the early stage of process synthesis and in the absence of an adequate amount of data. It would be therefore advantageous for designers if they were able to assess safety aspects in a continuous manner for retrofitting design purposes as well as appraising innovative alternatives. In this work, a newly developed Inherently Safer Design Tool (i-SDT) has been applied to identify reliable and safer operating conditions while implementing a cogeneration (COGEN) unit as a flare utilization alternative. In the illustrative case study, the COGEN unit has been accompanied by an ethylene process to act as an additional utility provider by using some portion of the unburn hydrocarbon streams. These streams were available from several flaring locations of the plant during different routine/abnormal cases. The objective of this work is to conduct a comprehensive techno-economic and environmental

performance analysis by utilizing a multi-objective optimization framework along with the necessary set of process constraints derived from the safety perspective offered by i-SDT. The illustrative case study considered here showed that the proposed i-SDT tool could estimate the limits associated with key safety parameters (flammability, toxicity, explosiveness, and reactivity) by explicitly considering operating conditions. Later, these operating limits are explicitly embedded as safety constraints into the optimization algorithm to assess the techno-economic, environmental and safety performance profiles of the process system under consideration.

- **Keywords:** Flare management; Inherent safety; Property integration; Risk quantification; Process design; Early-stage process synthesis; Accident and incident investigation

Xin-ge Qi, Haiqing Wang, Yiliu Liu, Guoming Chen. *Flexible alarming mechanism of a general GDS deployment for explosive accidents caused by gas leakage*. Pages 265-272.

Gas detection system (GDS) is critical for identifying and suppressing the flammable or hazardous gas leaked by incidents. The spread of a flammable gas cloud is susceptible to external factors and highly uncertain, but the GDSs deployed today often raise alarms based on certainty. It means that the threshold value set in a GDS for triggering alarms is a constant. Such an approach sometimes cannot accurately determine the leakage location, and so it may result in a great delay of gas detection. To reduce the risk of gas leakage, this paper proposes a flexible triggering mechanism for GDSs, where an alarm is raised or not depending on the number of sensors whose reading are reaching or closing to the preset threshold. An equivalent gas cloud (EGC) model is introduced here to provide design inputs for such a flexible triggering GDS. The volume and location distribution of an EGC are estimated with the Gaussian dispersion model, based on the changes of wind speed and direction. A case study in a terminal station of LNG is conducted, to illustrate the effectiveness of the new approach. The findings show that the flexible triggering mechanism is able to make alarms of a GDS more accurate, and meanwhile avoiding unnecessary measures, which can effectively optimize alarming thresholds.

- **Keywords:** Leakage; EGC; Explosion; Gas detection; Flexible alarming mechanism

Robert J. Bellair, Lawrence Hood. *Comprehensive evaluation of the flammability and ignitability of HFO-1234ze*. Pages 273-284.

Hydrofluoroolefin 1234ze (1,3,3,3-Tetrafluoropropene) is a fluorinated hydrocarbon introduced as a low global warming potential alternative for HFC-134a (1,1,1,2-tetrafluoroethane) and is classified as mildly flammable (A2L). Definition of appropriate engineering controls and electrical area classification requires accurate knowledge of the flammable properties of a material. Gaps and conflicts in published flammability data for HFO-1234ze are a concern for defining safe handling practices and appropriate layers of protection. The data available in literature has been compiled and analyzed to understand the sources of the data variability and the conditions under which HFO-1234ze will pose a flammability hazard. New data on the minimum ignition energy at 25C, flammable limits at 25C, and maximum experimental safe gap at 40C is also reported here and discussed in context with the large body of data from literature. It is proposed that much of the data measured at ambient conditions in the absence of water vapor does not effectively measure the true limits of flame propagation. Additionally, it appears that ignition limitations, and potentially other design factors, in the current standard test methods may result in the inaccurate measurement of flammable limits for HFO-1234ze under some conditions. It is concluded that HFO-1234ze can be safely handled when

appropriate engineering controls are implemented based on a thorough process safety risk assessment.

- **Keywords:** 1234ze; Flammability; A2L; Refrigerant

Byunggon Jung, Chang Jun Lee. *Plant layout and blast wall optimization with the consideration of operating conditions and potential explosions*. Pages 285-293.

Plant layout research contributes to reducing plant construction costs. In general, these problems have been solved by mixed integer non-linear programming (MINLP) models based on objective functions and various constraints. Moreover, many researchers have tried to combine safety issues for reducing expected losses generated by potential accidents in construction costs. However, these combinations of the objective function are very difficult and subjective, since there is no certain definition of the bias parameter that controls the trade-off between construction cost and the expected losses from potential accidents. In addition, in the real engineering industry, safety issues for mitigating potential accidents are considered after the overall plant layout has been determined. Through consider real engineering procedures, this study aims to provide systematic procedures for how to determine the position of plant equipment, and a safety device (blast walls). This problem is designed using two-step optimization approaches. The first step is to investigate the optimal locations of process equipment by considering operational costs and pipeline installation to minimize the construction costs and satisfy various constraints. The second step is to determine the optimal position of blast walls to maximize the mitigation effects of potential explosions. A case study is illustrated to verify that the proposed approach can provide optimal solutions for the locations of plant equipment and blast walls and can be easily applied in other processes.

- **Keywords:** Plant layout; MINLP; Blast walls; Original PSO technique

Nattee Akkarawatkhoosith, Apichart Srichai, Amaraporn Kaewchada, Chawalit Ngamcharussrivichai, Attasak Jaree. *Evaluation on safety and energy requirement of biodiesel production: Conventional system and microreactors*. Pages 294-302.

Commercial biodiesel production through transesterification of refined bleached & deodorized palm oil (RBDPO) with methanol is commonly performed in macroscale reactors. This work focused on the comparison of biodiesel production system in terms of production efficiency and safety evaluation for both conventional and microreactor systems based on the industrial production capacity of 20,589.29L/h. Our demonstration of the laboratory biodiesel production provided high quality of biodiesel comparable to the commercial biodiesel. Design of microreactor system for scaling-out to industrial capacity was performed. The simple layout of microreactor system provided great flexibility for operation and maintenance. Less energy consumption and a small number of operators relative to the conventional biodiesel production plant are required. Safety evaluation based on HAZOP and FMEA suggested that the microreactor system was relatively safer than that of the conventional one. The risk can be further reduced by regularly maintaining and calibrating equipment according to preventive maintenance schedule.

- **Keywords:** Biodiesel; Microreactor; Safety assessment; Process efficiency; Safety management

Jianhua Zhou, Haipeng Jiang, Yonghao Zhou, Wei Gao. *Flame suppression of 100 nm PMMA dust explosion by KHCO3 with different particle size*. Pages 303-312.

Flame suppression mechanism of KHCO3 for 100nm PMMA dust explosions was investigated experimentally and computationally. The effect of KHCO3 particle size on the suppression efficiency was examined. The study revealed that the larger the proportion of added KHCO3, the more significant the suppression effect on flame, for KHCO3 particles with a fixed particle size distribution. The suppression effects were significantly increased with the decreasing of KHCO3 particle size distributions. For endothermic mechanism, when the KHCO3 particles with three particle sizes were mixed with 100nm PMMA, the heat absorption peaks exhibited at the initial stage, in which the heat absorption values were 28J/g, 26J/g and 21J/g, respectively. A kinetics model was established to reveal the chemical suppression mechanism. It was presented that the mole fractions of key flame radicals (H and OH) were obviously reduced during the chain reaction processes with the addition of KHCO3. For KHCO3 particles, the formation of catalytic cycle K ⇔ KOH converted H and OH radicals into a stable combustion product H2O, resulting in a lower flame speed and flame temperature.

- **Keywords:** Nano-PMMA dust explosion; Explosion suppression; Flame propagations; Suppression mechanisms

Yue Han, Xingwei Zhen, Yi Huang, Jan Erik Vinnem. *Integrated methodology for determination of preventive maintenance interval of safety barriers on offshore installations*. Pages 313-324.

Preventive maintenance (PM) is an essential strategy to ensure the integrity of safety barriers and process safety on offshore installations. However, determination of the maintenance interval is challenging. Inadequate maintenance is likely to increase the unreliability of safety barriers and major accident risk, while excessive maintenance may increase personnel exposure and operational risk. In addition, it is highlighted that the reduction of maintenance cost should also be taken into consideration. In this study, a new integrated methodology is proposed to determine the maintenance interval of a specific group of safety barriers, which require periodic testing. Specifically, the study deals with the trade-off between risk increase and reduction associated with maintenance, and optimizes the allocation of maintenance cost. It aims at minimizing the total risk level whilst reducing the maintenance cost. The dynamic data model is established first to predict the state and trend of risk level for the safety barriers. Then, the classification model is established to classify the risk level and optimize the allocation of maintenance cost. Finally, the maintenance decision model is established to balance the maintenance-related risks. The proposed methodology is tested by a case study which is to determine the recertification interval of PSVs on a specific offshore installation on the Norwegian Continental Shelf (NCS). It is demonstrated that the proposed methodology is effective in determining the PM interval. The methodology is also useful in minimizing the total risk level of the safety barriers and reducing the maintenance cost per unit time.

- **Keywords:** Safety barrier; Risk level prediction; Maintenance interval; Maintenance cost; Bayesian

John Lee, Ian Cameron, Maureen Hassall. *Improving process safety: What roles for Digitalization and Industry 4.0?* Pages 325-339.

Process safety and risk management remain a significant challenge for the process and manufacturing industries. Digital systems have been applied over many decades to assist in process safety management throughout the lifecycle of a process plant. There has been much hype in recent years regarding Industry 4.0, digitalization and digital twins regarding the transformative potential that exists within these technologies to improve operational performance and reduce process safety accidents. In this article, a fundamental systems thinking approach is applied to the implementation of the digital twin within the process industries. The importance of having a standardized language and

ontology, such as ISO15926, enables the use of reasoning engines and the ability to interconnect models and systems across the process and product lifecycle. We discuss use-cases and forms of the digital twin to improve safety within the process industries. A specific focus shows how an operator training simulator and its embedded dynamic models are applied within this environment. The article concludes with a summary of process safety related opportunities and threats associated with the application of digitalized dynamic models in industry.

- **Keywords:** Process safety; Digital twin; Digitalization; Industry 4.0; Models; Life cycle; ISO15926

Mostafa Shoorangiz, Mohammad Reza Nikoo, Marjan Salari, Gholam Reza Rakhshandehroo, Mojtaba Sadegh. *Optimized electro-Fenton process with sacrificial stainless steel anode for degradation/mineralization of ciprofloxacin*. Pages 340-350.

In this study, an electro-Fenton (EF) process with auto generation of Fenton`s catalyst (Fe2+) was proposed and its applicability in degradation and mineralization of Ciprofloxacin (CIP) antibiotic was examined. A graphite-felt sheet was used as cathode for continuous electro-generation of H2O2 and a trifle stainless steel plate (AISI 304) was used as sacrificial anode to provide ferrous catalyst. Effect of various operating parameters including current intensity (5–100mA), reaction time (5–25min), initial CIP concentration (10–150mg/L) and initial pH (2–7) was investigated using Response Surface Methodology (RSM). Central Composite Design (CCD) under RSM was utilized to model the two main responses, namely, CIP and COD removals. Simultaneous optimization of responses under current intensity of 75mA, treatment time of 20min, initial CIP concentration of 45mg/L and initial pH of 5 showed that 95.1% and 57.4% of CIP and COD removal efficiency could be achieved, respectively. High coefficients of determination (R2), for CIP and COD removal efficiency (0.92 and 0.94, respectively) indicated strong predictive capability of the models. BOD5/COD ratio, as an index of biodegradability, increased sharply from 0 to 0.42 under optimal condition. Two energy models, Electrical Energy Consumption (EEC) and EEC per unit COD removal, were introduced and the effect of operating parameters on them was evaluated. The intermediates of CIP degradation in aqueous solution were identified using ion chromatography and liquid chromatography coupled with mass spectrometry (LC–MS).

- **Keywords:** Central composite design (CCD); Ciprofloxacin antibiotic; Electro-fenton; Optimization; Sacrificial anode

Shouqing Lu, Chengfeng Wang, Qingquan Liu, Yongliang Zhang, Jie Liu, Zhanyou Sa, Liang Wang. *Numerical assessment of the energy instability of gas outburst of deformed and normal coal combinations during mining*. Pages 351-366.

The complexity of the coal and gas outburst process makes the gas outburst mechanism difficult to understand, leading to serious disasters of coal and gas outbursts in China. However, the presence of deformed coal may promote the occurrence of coal and gas outbursts, and several normal coal layers and deformed coal layers often occur at the same location. To better assess the energy instability of gas outbursts of coal combinations, the coal and rock were assumed to be homogeneous, isotropic mediums, and the deformation of coal and rock was assumed to be infinitesimal. Then, ignoring the influence of the change of gas pressure on the stress field during the process of gas emissions, the distribution of the horizontal stress, plastic failure and gas pressure in the coal in front of the roadway were analyzed in three different cases. The results show that there will be a large horizontal tensile stress between the normal coal and deformed coal, which may make plastic failure extend from the deformed coal to the normal coal

through the interface. Due to plastic failure, the permeability of deformed coal in coal combinations will increase. Moreover, the deformed coal itself not only enables gas to migrate rapidly but also increases the gas emissions of the normal coal adjacent to the deformed coal. Then, a new model of gas outburst energy and an energy criterion of outburst were established. It was found that the total outburst energy of the normal coal in combinations is approximately 149 times that of a normal coal monomer, so the deformed coal increases the total outburst energy of the normal coal in coal combinations. In regard to the outburst energy of coal combinations, the desorbed gas expansion energy is the highest, which is 1–6 times the elastic energy and 5–17 times the gas expansion energy. In addition, measures should be taken to first reduce the expansion energy caused by desorbed gas, and second measures should be taken to reduce the elastic energy caused by ground stress. Finally, a series of control measures of gas outbursts for different coal seams were proposed. These research results, which were obtained under certain assumptions, can provide a theoretical basis for the selection of measures for the control of coal and gas outbursts of coal combinations.

- **Keywords:** Coal combination; Gas outburst; Energy instability mechanism; Deformed coal

Qiang Liu, Wen Nie, Yun Hua, Huitian Peng, He Ma, Shuai Yin, Lidian Guo. *Long-duct forced and short-duct exhaust ventilation system in tunnels: Formation and dust control analysis of pressure ventilation air curtain*. Pages 367-377.

To decrease the high concentration dust in tunnels with a long-duct forced and short-duct exhaust ventilation system, airflow and dust field migration behaviours, when different distances between pressure ventilation outlet and tunnel face are involved, are analysed with the application of numerical simulation and field measurements in this study. The formation principle of air curtain and the dust control rule in tunnels with a long-duct forced and short-duct exhaust ventilation system are also elaborated and the conclusions can provide the guidance for dust control in tunnels. Numerical simulation shows that the formation of pressure ventilation air curtain is mainly determined by the distance between the pressure ventilation outlet in eddy airflow field and tunnel face. The mathematical relationship of the diffusion distance of high concentration dust is determined as a function of the distance between the pressure ventilation outlet and tunnel face. Field measurements are carried out in the second auxiliary tunnel of Longgu to determine the dust concentration along the tunnel. The results show that when the distance between the pressure ventilation outlet and tunnel face is 35 m, the dust concentration is lowered to less than 18.2 mg/m3, demonstrating the effective dust control of the pressure ventilation air curtain. It also ensures the safety of tunnel production and the protection of the workers' physical health, and reduces the occurrence of pneumoconiosis.

- **Keywords:** Long-duct forced and short-duct exhaust ventilation system; Tunnel; Pressure ventilation air curtain; Dust control; Eddy airflow field