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Quantitative health risk assessment of inhalation exposure to automobile foundry dust

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Abstract With a growing awareness of environmental protection, the dust pollution caused by automobile foundry work has become a serious and urgent problem. This study aimed to explore contamination levels and health effects of automobile foundry dust. A total of 276 dust samples from six types of work in an automobile foundry factory were collected and analysed using the filter membrane method. Probabilistic risk assessment model was developed for evaluating the health risk of foundry dust on workers. The health risk and its influencing factors among workers were then assessed by applying the Monte Carlo method to identify the most significant parameters. Health damage assessment was conducted to translate health risk into disability-adjusted life year (DALY). The results revealed that the mean concentration of dust on six types of work ranged from 1.67 to 5.40 mg/m^3. The highest health risks to be come from melting, cast shakeout and finishing, followed by pouring, sand preparation, moulding and core-making. The probability of the risk exceeding 10^{-6} was approximately 85%, 90%, 90%, 75%, 70% and 45%, respectively. The sensitivity analysis indicated that average time, exposure duration, inhalation rate and dust concentration (C) made great contribution to dust health risk. Workers exposed to cast shakeout and finishing had the largest DALY of 48.64a. These results can further help managers to fully understand the dust risks on various types of work in the automobile foundry factories and provide scientific basis for the management and decision-making related to health damage assessment.

Keywords Automobile foundry · Dust · Health risk assessment · Disability-adjusted life year · Monte Carlo simulation

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Introduction

In recent years, the automobile manufacturing industry has become one of the most important pillars supporting the global economy, and the foundry trade accounts for a large proportion of the its work. The automobile industry is vital to the world economy and

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promoting social progress, but also experiences many occupational accidents and negative effects on the health of the workers involved. Dust is a major the air pollutant (Shen et al. 2009) and one of the industry's most important occupational hazards, arising to varying degrees in the stamping, welding, coating and assembly processes (Paiman et al. 2013), and is particularly serious in the foundry working environment (Riaz et al. 2017). Dust can cause such respiratory problems as cardiovascular disease, cerebrovascular disease, acute respiratory infections and chronic obstructive pulmonary disease (Rushton 2007; Hsieh and Liao 2013) and, in severe cases, lead to ischaemic heart disease and pneumoconiosis (Chen et al. 2012). It is necessary, therefore, to accurately identify and assess the health risks of dust to help enhance occupational health management in the automobile foundry working environment and consequently protect worker health.

Dust health risk assessment was widely used in the coal mining and construction industries. For the coal mining industry, Donoghue (2001), for example, established risk ratings of the occupational damage factors of the coalmines, ranking the factors involved semi-quantitative methods. Other studies analysed dust hazards from a medical point of view, probing into the relationship between pathology and mortality pneumoconiosis (Tamura et al. 2015; Li et al. 2015; Schenker et al. 2009). The methods for evaluating dust health damage were proposed based on Life Cycle Assessment (LCA) theory and related knowledge of environmental health and pathology (Tong et al. 2013; Harder et al. 2015). For the construction industry, several studies have focused on the effects of control measures on building construction dust (Harrad et al. 2006; Kuusisto et al. 2007; Van Deurssen et al. 2014). In addition, many researchers have also used deterministic methods to quantify dust health damage; Zhang et al. (2007), for example, evaluated particulate pollution risk and quantified the public health damage caused by the 2000–2004 air emissions in Beijing based on the exposure–response function. Li et al. (2010, 2013) and Tong et al. (2018) established a construction dust health damage evaluation framework for different types of construction activities and examined the social willingness to pay, while the risk of pneumoconiosis hazard was evaluated in the stone machining industry using an occupational health risk assessment model provided by the International Council on Mining and Metals (ICMM) (Al-Anbari et al. 2005).

Automobile foundry industry studies mainly measured and monitored the concentration of dust and identified dust hazards in the working environment (Krishnaraj 2015; Andersson et al. 2008). Song et al. (2014), for example, measured particle concentration distribution in a foundry workshop and analysed the characteristics of foundry dust pollution considering total dust control in the industry; Hamzah et al. (2014) determined the relationship between metal dust exposure and the respiratory health of male foundry workers; Omidianidost et al. (2016) evaluated the risk of lung cancer in foundry workers for different processes based on relative linear regression models; and logistic regression models have been fitted for analysing related factors of adverse health effects to predict the relationship between the incidence of pneumoconiosis, cumulative dust exposure and length of employment of foundry workers (Rosenman et al. 1996; Zhang et al. 2010; Wang et al. 2013). However, to our knowledge, few studies have been undertaken on the health risk caused by dust in the foundry working environment.

Further, quantitative health risk analyses are indispensable to evaluate potential human risk and to provide scientific basis for the management and decision-making. Generally speaking, there are two methods for health risk assessment: deterministic and probabilistic risk assessment approaches (Öberg and Bergbäck 2005; Man et al. 2014; Phan et al. 2016). For the former method, health risks are calculated based on the reasonable maximum exposure parameters and pollutant contents; the results may be over- or underestimated because health risk assessment retains large uncertainties (Peng et al. 2016; Li et al. 2012; De Miguel et al. 2007). In contrast, the latter method attempts to characterize uncertainty and variability according to the statistical distribution of the exposure parameters (Sander et al. 2006). Hence, probabilistic risk assessment method was employed to evaluate the dust health risk in this study.

We examined an automobile foundry factory located in Hubei Province in China as a case study. The main objectives of this study were to: (1) determine the contamination levels of dust on six types of work in the automobile foundry factory; (2) evaluate the probabilistic health risk of dust to workers by considering the uncertainty of both dust concentration and exposure parameters; (3) identity the influential variables in health risk assessment; and (4) estimate the health impairment of automobile foundry dust to the practitioners. The findings of this research may be helpful for manager to formulate health risk management decisions in the automobile foundry industry.

Materials and methods

The selected foundry and production process

A foundry factory of a large-scale automobile manufacturer in Hubei Province was selected for this study. This factory mainly produces commercial vehicles parts. The process flow diagram of automobile foundry is displayed in Fig. 1. A simple description of production process is as follows: first, the materials containing pig iron, waste castings and scraps are melted in the melting furnaces and then transferred and dumped into the pouring furnace. Next, the molten metals in the pouring furnace are detected and adjusted according to the requirement of the composition ratio. Finally, these molten metals are poured into the mould, and after cooling, a new casting is obtained through further cleaning and polishing. Sand preparation, melting, core-making, moulding, pouring and cast shakeout and finishing were not only the main processes of the foundry production, but also produced a large amount of dust. There are two sources of dust generation: one is the physical process with sand preparation and cast shakeout and finishing, and the other is the direct or indirect heating process, such as melting, moulding, core-making and pouring.

Sampling sites and sample collection

The dust samples were collected from August 2016 to November 2016 in the foundry working environment, which lasted for 3 months. The sampling process followed the national standard Specifications of air sampling for hazardous substances monitoring in the workplace (Ministry of Health 2004). We set six sampling points (S1–S6) in foundry workshop: S1 located in the sand preparation areas, S2 located near the pouring table, S3 was between two melting furnaces, S4 was close to the core-making areas, S5 and S6 located in the moulding and cast shakeout and finishing areas, respectively. The layout of sampling sites is illustrated in Fig. 2. In this study, total suspended particulate matter (TSP) with particle size less than 100 μm was selected as the monitoring indicator of dust. The dust sampler (HXF-35, Yancheng, China) equipped with perchloroethylene filter membranes (37 mm diameter, China) was employed for dust sampling with a flow rate of

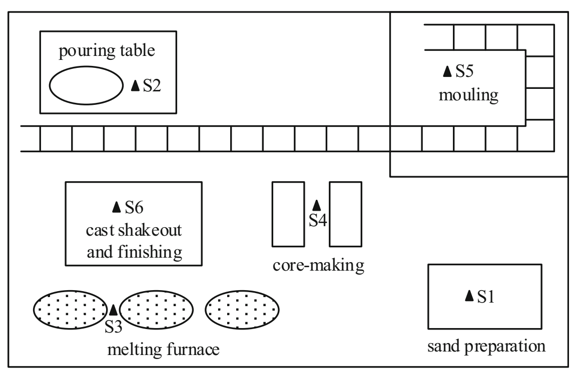

Fig. 2 Location of the sampling points in foundry workshop

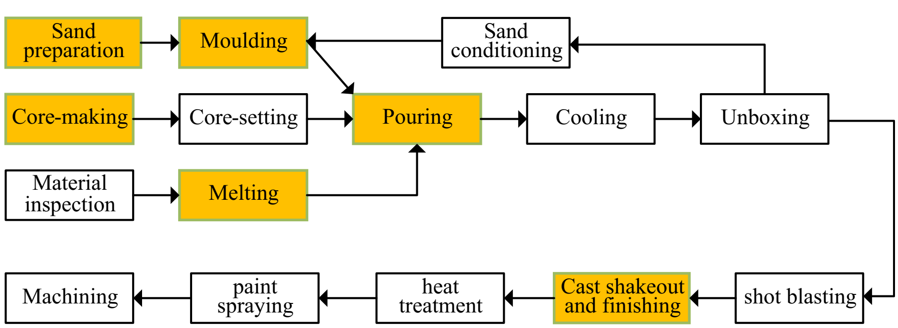

Fig. 1 Foundry production process flow

Table 1 Content of free silica in dust (%)

Type of work	Mean	Range	Type of work	Mean	Range
Sand preparation	30.6	14.7–80.5	Core-making	70.2	56.3–87.4
Cast shakeout and finishing	22.8	21.9–23.9	Melting	21.5	19.3–24.0
Moulding	31.4	19.8–40.3	Pouring	21.5	20.3–31.6

20.0 L/min. We conducted sampling for three times, respectively, in 10:30–10:45, 14:30–14:45 and 17:00–17:15 every working day and each sampling lasts for 15 min. The dust concentration was calculated using a filter membrane incremental method. The free silica content in the dust was determined by the pyrophosphate method, as summarized in Table 1. A total of 276 dust samples were collected: 53 from the sand preparation, 66 from the cast shakeout and finishing, 41 from the moulding, 31 from the core-making and 52 from the melting and 33 from pouring in foundry.

Sample analysis

The analysis process of dust samples was carried out according to GBZ/T192.1-2007 (Ministry of Health 2007). Before sampling, all filter membranes were placed in desiccator for 2 h, then numbered and weighed to record the weight of these filter membranes. At the sampling point, the dust sampler equipped with filter membrane was as close as possible to foundry workers. After sampling, the filter membrane was accurately weighed using a microbalance with a detection limit of 0.01 mg. The weight of the filter membranes and the volume of air samples were recorded for the calculation of the dust concentration in the foundry working environment.

Health risk assessment modelling

This study mainly evaluates dust health risks to workers in automobile foundry factory. The exposure pathways of pollutants to human health mainly involve three routes: the inhalation, ingestion and dermal contact. From a recent literature review, it was found that the inhalation pathway is the main pathway in which air emissions enter the human body (Dong et al. 2014; Zhang et al. 2014; Tong et al. 2018). Thus, the dust health risks to workers through the inhalation pathway are the focus of this paper.

The establishment of the evaluation model was based on a combination of the United States Environmental Protection (USEPA) recommended inhalation health risk assessment and health damage quantitative assessment methods. The inhalation health risk assessment method estimates the rate of harmful factors causing negative influence on humans according to the characteristics of the hazardous substances and dose–response relationships and converts the concentration of hazardous substances into health risks (USEPA 2003). The exposure parameter in the evaluation model was used to describe the dose of human body exposure to external substances through air inhalation and in turn quantify the dose of harmful substances absorbed into the human body from the environment (Wang et al. 2009). The health damage quantitative assessment method was mainly used to quantify the damage caused by harmful substances to the human body and converts the health risk into life-lost caused by the damage endpoint, with the evaluation results expressed in disability-adjusted life years (DALY) (Murray and Lopez 1997). Figure 3 illustrates the details of the health damage model.

Exposure dose of dust

According to the exposure parameter method, the monitored dust concentration was converted to the average daily dose (ADD) of automobile foundry workers. The ADD is expressed as Eq. (1):

$$\mathrm{ADD} = \frac{\mathrm{C} \cdot \mathrm{IR} \cdot \mathrm{ED} \cdot \mathrm{EF} \cdot \mathrm{ET}}{\mathrm{BW} \cdot \mathrm{AT}} \tag{1}$$

where ADD is the average daily dose of automobile foundry workers (mg/kg d^{-1}); C is the dust quality concentration in foundry working environment (mg/m^3); IR is the inhalation rate of foundry workers (m^3/h); ED is the exposure duration (a); EF is the exposure frequency (d/a); ET is the exposure time (h/d); BW is the body weight (kg); and AT is the average time (d).

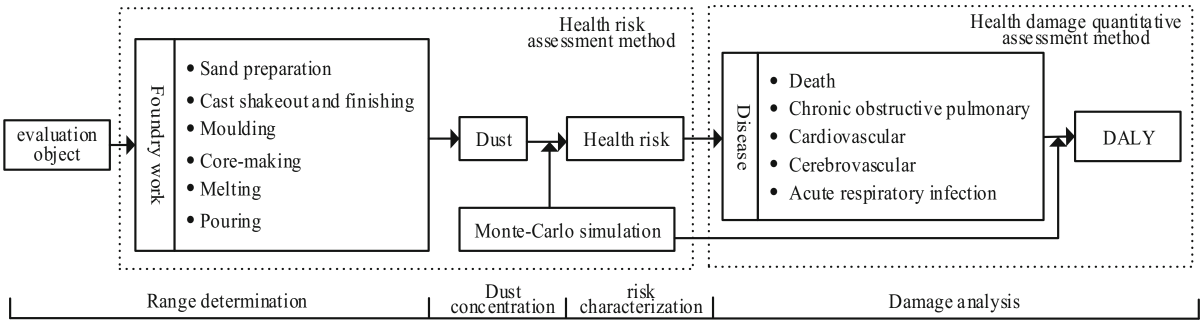

Fig. 3 Health damage model of dust

Health risk of dust

The health risk was assessed using the following model according to the existing health risk assessment system (Rice et al. 2000; USEPA 1989), as shown in Eq. (2).

$$R = \frac{\mathrm{ADD}}{\mathrm{RfD}} \times 10^{-6} \quad (2)$$

where R is the health risk of dust (unitless) and RfD is a reference dose of dust (mg/kg d^{-1}).

Dust contains multiple components, such as polycyclic aromatic hydrocarbons (PAHs) (Najmeddin and Keshavarzi 2018), Pb, Cd, V, Ni, Cu, Cr, Zn (Jiang et al. 2017; Zhang et al. 2017), organic and elemental carbon, and inorganic ions (Cheung et al. 2011). In particular, there would be many potentially toxic metals in dust in automobile foundry industry areas. Dusts are usually present in the environment as mixtures. However, the evaluation and quantification of combined effects of multiple components were not commonly studied (Qiming et al. 2012). To our knowledge, some recent studies used the RfD of PM_{10} and dust for health risk evaluation (Xiang et al. 2015; Li et al. 2015). Because the content of free silica in dust is more than 10%, the dust in foundry working environments is silica dust (Table 1). Thus, we applied the RfD of silica dust for health risk assessment in this study. The RfD value of silica dust is 0.40 mg/kg d^{-1} (Tong et al. 2018).

Health damage of dust

The DALY was developed by the World Health Organization (WHO) to assess the global burden of disease (Murray 1994). It is a metric the combines both time lost due to premature mortality and morbidity (non-fatal health problems). One DALY equates to one lost year of healthy life, which is equivalent to only a 90% full capacity and survival for 10 years. Based on pathobiology, environmental toxicology and the Life Cycle Assessment method, a health damage quantitative assessment method was established to evaluate the health impact of dust in automobile foundry factories. Dust can cause several respiratory diseases, like chronic obstructive pulmonary disease, cardiovascular disease, cerebrovascular disease, acute respiratory infections and even death. The health risks were proportionally distributed to these diseases through effect analysis and damage analysis, and the health risks are eventually unified into DALY to characterize specific health hazards of dust. The DALY is expressed as Eq. (3):

$$\mathrm{DALY} = n \cdot \sum_i R \cdot Q_i \cdot W_i \cdot L_i \cdot P \quad (3)$$

where Q_i is the risk factor for disease category i, namely the proportion of the risk in the distribution of various types of damage (unitless); W_i is the effect factor of disease category i and takes values between 0 and 1 (unitless); L_i is the damage factor for disease category i, namely average life expectancy (a); P is the number of people affected by specific diseases (unitless); and n is the frequency of human exposure (d).

Referring to the relevant literature and data (Zhang and Wu 2008; Li et al. 2015), the relevant parameter values of the risk factor Q and the effect factor W were obtained. The value of the damage factor L usually depends on the evaluation object, automobile foundry workers are mostly men from all over the country, their damage factor values are shown in the last column in Table 2, and the average life expectancy

Table 2 Relevant parameter values of dust health damage

Disease endpoints	Q^a	W^b	L^c
Death	0.13	1.00	42.2
Chronic obstructive pulmonary disease	0.16	0.15	10
Cardiovascular disease	0.16	0.24	37.2
Cerebrovascular disease	0.20	0.20	37.2
Acute respiratory infections	0.35	0.08	0.04

[a]The proportion of various types of disease caused by dust

[b]The disability weight of various types of disease

[c]The average life expectancy of field workers

values are derived from the China Statistical Yearbook (2011).

Input parameters

The exposure parameters play a critical role in human body exposure and health risk assessment. Thus, some human body exposure parameters were included in the foundry dust occupational health risk assessment, including inhalation rate, exposure duration, exposure frequency, exposure time, body weight and average exposure time. The exposure parameters contributed greatly to the accuracy of health risk assessment due to differences in the exposed populations and areas and, if improperly made, can result in larger error seriously affecting the health risk assessment.

We interviewed all workers from six types of work in automobile foundry factory. Forty people were selected from sand preparation, 339 people from the cast shakeout and finishing, 104 people from the moulding, 225 people from the core-making, 90 people from the melting and 32 people from the pouring to obtain the exposure parameters of foundry workers. Through the investigation of the working condition to the foundry workers, the data such as exposure time, exposure frequency, average time and exposure duration of the foundry workers were recorded. The Crystal Ball software performs goodness-of-fit tests (Chi-squared, Kolmogorov–Smirnov and Anderson–Darling) on the statistical values to analyse what distribution these exposure parameters conforms to. In this study, triangle distribution had the best fit for exposure time, exposure frequency, average exposure time and exposure duration based on Anderson–Darling test. The values of the other parameters in Eq. (1) were obtained according to the study on human exposure factors conducted by Wang et al. (2009) and Chen and Liao (2006). These data mainly derived from the large-scale empirical data and related research in China. Relevant parameter values of foundry workers are shown in Table 3.

Methodology

To obtain dust health risks of workers that were exposed to various types of work and to evaluate the uncertainty and influence of both dust concentration and exposure parameters, a probabilistic risk assessment model was developed based on Monte Carlo simulation. As one of the most common methods, Monte Carlo simulation is usually used to deal with the uncertainties associated with many risk-related problems (Qu et al. 2015; Othman et al. 2018). It provides a quantitative way to evaluate the probability distributions of environmental health risks. This process was performed using Crystal Ball software. Some studies have shown that 5000 iterations are sufficient to ensure the stability of results and the results are even more accurate with 10,000 simulations (Chiang et al. 2009). Therefore, the number of iterations was set to 10,000, and the confidence interval was set to 95%.

Sensitivity analysis was conducted to investigate the influence of the exposure variables and dust

Table 3 Relevant parameter values of foundry workers

Exposure parameters	Abbreviation	Unit	Distribution	Probable value	Min	Max	SD	References
Inhalation rate	IR	m^3/h	Triangular	1.9	0.95	2.85		Wang et al. (2009)
Exposure duration	ED	a	Triangular	30	5	45		This study
Exposure frequency	EF	d/a	Triangular	292	264	324		This study
Exposure time	ET	h/d	Triangular	9.07	8	10.5		This study
Body weight	BW	kg	Normal	56.8			5.8	Chen and Liao (2006)
Average time	AT	d	Triangular	10950	1825	16425		This study

Table 4 Concentration (mg/m^3) and dispersity (%) of dust in foundry working environments

Type of work	Dust concentration			Dust dispersity			
	Distribution	Mean	SD	< 2 μm	2–5 μm	5–10 μm	≥ 10 μm
Sand preparation	Normal	2.93	1.11	39	40	16	5
Cast shakeout and finishing	Normal	4.37	0.50	56	24	17	3
Moulding	Normal	2.37	0.25	71	23.5	4	1.5
Core-making	Normal	1.67	0.85	61	22	11	6
Melting	Normal	5.40	2.17	78.5	16.5	3	2
Pouring	Normal	3.90	0.69	81.5	14.5	3	1

concentrations on health risks, where a positive coefficient indicates that the variable has a positive effect on the prediction result, and a negative coefficient indicated the opposite effect. The greater the absolute values, the greater the impact on the risk. The figures of risks and sensitivities are further processed with Origin Pro 2017 software.

Results and discussion

Monitoring results and discussion

The probability distribution of dust concentration was mainly obtained by Crystal Ball software. In this study, normal distribution had the best fit for dust concentration in various working environments based on Anderson–Darling test. The descriptive statistics of dust contamination levels in the foundry working environments are shown in Table 4. The mean concentration of dust on six types of work ranged from 1.67 to 5.40 mg/m^3. The pollution levels for the dust occurred in the following order: melting > cast shakeout and finishing > pouring > sand preparation > moulding > core-making in the sampling sites.

Core sand contained a certain amount of moisture and liquid substances, and less dust was generated during operation of core-making; therefore, the dust concentration in the environment of core-making was the lowest. For sand preparation and moulding, some materials such as new sand, old sand, binder and auxiliary materials were mixed by the dry way, so the dust pollution was more serious than that in the environment of core-making. Furthermore, it is inconvenient to add some dust-proof covers in the moulding station because of the limitation of the production conditions, which further aggravates the diffusion of dust; the dust concentration of the moulding was higher than in the sand preparation. Since the cupola with the highest dust generation is located in the melting area, the workers exposed to melting suffered the most serious dust pollution.

The dispersity of foundry dust was determined by microscopic image analysis method. The results indicated that the proportion of particles with particle size < 5 μm exceeded 79% in foundry working environments. For various types of work, the proportion of particles with particle size < 10 μm ranged from 94 to 99%. To date, particles that have the most impact on human health effects have been acknowledged to be those less than 10 μm in diameter (Kim et al. 2015). These particles can be directly inhaled into the lung of human due to their excessive penetrability.

Health risks of dust

The results of the dust health risk simulations are shown in Figs. 4 and 5 and Table 5. The health risk values for melting and cast shakeout and finishing followed a lognormal distribution with geometric means 3.84×10^{-6} and 3.10×10^{-6} and geometric standard deviations 3.31×10^{-6} and 2.02×10^{-6}, respectively, with maximum risks of 5.25×10^{-5} and 2.31×10^{-5} (Table 5). According to USEPA, the acceptable health risk value is 1.0×10^{-6} and the upper limit value is 1.0×10^{-4} (Cheung and Wong. 2006; Liu et al. 2016; Wang et al. 2017; USEPA 1989). It indicates that health harm is acceptable when the risk value is below 1.0×10^{-6}, while the risk value exceeding 1.0×10^{-4} is considered that there would be a serious risk to the human body. For melting and cast shakeout and finishing, therefore, the

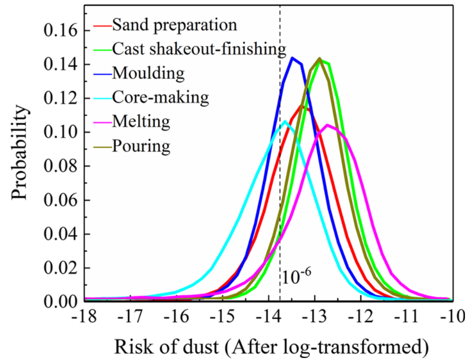

Fig. 4 Health risk of dust in all types of working environments

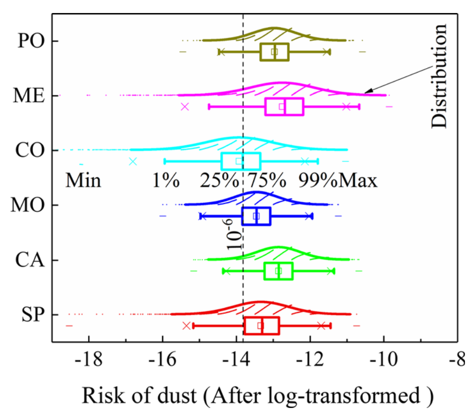

Fig. 5 Health risk of dust in all types of working environments. *SA* sand preparation, *CA* cast shakeout and finishing, *MO* moulding, *CO* core-making, *ME* melting and *PO* pouring

respective average values were 3.84 and 3.30 times the acceptable health risk—85% of health risk exceeding the acceptable health risk of melting and around 90% exceeding the acceptable health risk of cast shakeout and finishing. Therefore, the dust in those two types of working environment had potential health risk to human health.

The health risk values for pouring and sand preparation followed a lognormal distribution with geometric mean 2.78×10^{-6} and 2.07×10^{-6} and geometric standard deviation 1.84×10^{-6} and 1.61×10^{-6}, respectively. For pouring, the minimum value and the maximum value of health risks were 1.94×10^{-7} and 2.53×10^{-5}, respectively, indicating that 90% exceeded the acceptable health risk. For sand preparation, the maximum value of health risk was 2.17×10^{-5}, with 75% exceeding the acceptable health risk.

Table 5 Statistical values of health risk of all types of workers

Type of work	Min	Max	Mean	SD	Quartiles/% 5	25	50	75	95
Sand preparation	8.93×10^{-9}	2.17×10^{-5}	2.07×10^{-6}	1.61×10^{-6}	4.37×10^{-7}	1.03×10^{-6}	1.67×10^{-6}	2.63×10^{-6}	5.08×10^{-6}
Cast shakeout and finishing	2.61×10^{-7}	2.31×10^{-5}	3.10×10^{-6}	2.02×10^{-6}	9.78×10^{-7}	1.79×10^{-6}	2.63×10^{-6}	3.80×10^{-6}	6.84×10^{-6}
Moulding	1.13×10^{-8}	1.32×10^{-5}	1.70×10^{-6}	1.12×10^{-6}	5.37×10^{-7}	9.77×10^{-7}	1.44×10^{-6}	2.09×10^{-6}	3.79×10^{-6}
Core-making	4.03×10^{-10}	1.60×10^{-5}	1.21×10^{-6}	1.09×10^{-6}	1.25×10^{-8}	5.25×10^{-7}	9.62×10^{-7}	1.56×10^{-6}	3.14×10^{-6}
Melting	2.00×10^{-9}	5.25×10^{-5}	3.84×10^{-6}	3.31×10^{-6}	4.71×10^{-7}	1.74×10^{-6}	3.03×10^{-6}	5.02×10^{-6}	9.77×10^{-6}
Pouring	1.94×10^{-7}	2.53×10^{-5}	2.78×10^{-6}	1.84×10^{-6}	8.65×10^{-7}	1.60×10^{-6}	2.36×10^{-6}	3.41×10^{-6}	6.11×10^{-6}

The health risk values for core-making and moulding again followed a lognormal distribution with geometric mean 1.21×10^{-6} and 1.70×10^{-6} and geometric standard deviation 1.09×10^{-6} and 1.12×10^{-6}, respectively, 70% of health risk exceeding the acceptable health risk of moulding and approximately 45% exceeding the acceptable health risk of core-making. Although the health risks of moulding and core-making were relatively small, the probability of health risk values more than 10^{-6} was large, so the occupational health status of these workers needs to be of particular concern.

Qi et al.'s (2011) study of the distribution of occupational hazards and their effect on health in an investment casting enterprise found that silica dust exceeded the occupational exposure limits and the over standard rate reached 83.3%, but the health risk was not studied in depth. Our results are that, in addition to moulding, 70–90% exceeded the acceptable health risk of sand preparation, cast shakeout and finishing, core-making, melting and pouring, and the probability of health risk exceeded the acceptable 1.0×10^{-6} for all five cases, which was consistent with the standard-exceeding rate of dust in investment casting enterprises.

The dust health risk was simulated in all types of working environment, and the simulation results were compared and analysed. The results are shown in Fig. 5, the dust had obviously different impacts on foundry workers in different types of working environments, and the dust health risk on foundry workers from large to small was melting, cast shakeout and finishing, pouring, sand preparation, core-making and moulding. The health risk of melting was far higher than other types of work and 3.25 times larger than core-making, which implied that dust treatment should be the first consideration in the working environment of melting.

For a particular type of work, a health risk value can be obtained by deterministic analysis, but the dust health risk trends and overall situations cannot be forecasted in this way. As is demonstrated here, compared with the deterministic analysis, probabilistic risk assessment model can be used to evaluate the dust health risk to obtain the best distribution fitting, the average, maximum, minimum and different quantile values. Therefore, the dust health risk in different types of environments can be analysed comprehensively by probabilistic risk assessment method.

Sensitivity analysis

The results indicate that dust concentration is the most dominating factor causing dust health risks, with 69.31%, 67.56% and 58.07%, in workers exposed to core-making, melting and sand preparation, respectively (Fig. 6). Exposure duration also posed sensitive influence on dust health risk, while average time and body weight contributed a negative sensitivity.

Overall, the average time had the highest impact on dust health risk and exposure duration ranked second, followed by inhalation rate for workers exposed to cast shakeout and finishing, moulding and pouring in foundry. Among them, the sensitivity of inhalation rate was 35.72%, 36.95% and 33.72%, respectively. Similarly, average time and body weight, with − 58% and − 16%, respectively, have a negative effect for workers exposed to cast shakeout and finishing, moulding and pouring. The finding was in agreement with the previous study of Qu et al. (2015).

From the analysis of all data, a remarkable conclusion can be drawn. The same parameter had a different effect on dust health risk of workers exposed to different types of working environment; therefore, managers need to devise different measures and effective methods to reduce the dust risks involved. The health risks of workers exposed to sand preparation, core-making and melting, for instance, can most be reduced by controlling the dust concentration.

In brief, the average time, exposure duration, inhalation rate and dust concentration displayed relatively higher sensitivity and have a decisive effect on dust health risks, while those parameters, like body

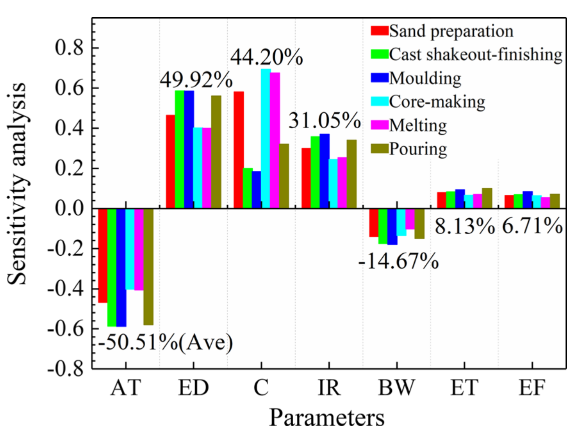

Fig. 6 Sensitivity analysis of dust health risk

Table 6 Statistical values of health damage (DALY) for all types of workers (a)

Type of work	Number	Min	Max	Mean	Quartiles/%				
					5	25	50	75	95
Sand preparation	40	0.01	37.70	3.89	0.80	1.93	3.21	4.95	9.35
Cast shakeout and finishing	339	2.95	386.63	48.64	15.88	28.04	40.83	59.06	107.40
Moulding	104	0.71	63.17	8.13	2.54	4.72	6.86	9.93	18.10
Core-making	225	0.01	143.33	12.07	1.11	5.30	9.47	15.92	31.60
Melting	90	0.01	182.27	15.84	1.74	7.03	12.51	20.73	41.07
Pouring	32	0.21	33.22	4.07	1.23	2.31	3.43	5.01	9.16

weight, exposure time and exposure frequency, had less effect.

Health damages of dust

Table 6 shows that dust health damage varies significantly for the six types of foundry workers. Compared with the other five types of workers, workers exposed to cast shakeout and finishing had the largest DALY of 48.64a, with workers exposed to melting ranked second at 15.84a, followed by workers exposed to core-making, moulding and pouring, with 12.07a, 8.13a and 4.07a, respectively. The DALY of the workers exposed to sand preparation was the smallest, with a value of 3.89a. Although dust health risk was the highest for workers exposed to melting, the dust health damage was not the highest due to the influence of the number of workers. This result indicates that the dust health damage was related to the number of workers.

Figure 7 shows the analytical results for the DALYs for different types of workers at the 95% confidence level. The DALY of the workers exposed to cast shakeout and finishing fell well outside the range of 15.88 $\sim$ 107.40a, indicating a high potential dust health damage, whereas workers exposed to sand preparation and pouring had a DALY ranging from 0.80 to 9.35a and 1.23 to 9.16a, respectively. The DALYs of the workers exposed to moulding were mostly in the 2.54–18.10a, 1.11–31.60a for core-making and 1.74–41.07a for melting.

Implications

Findings of the research reported in this paper have significant implications. According to many previous studies (e.g. Zhang et al. 2010), both engineers and social scientists have become increasingly interested in assessing the impact of dust on workers in the automobile foundry industry, with the level of occupational exposure to dust as a major air pollutant assessed by monitoring dust concentration data, for instance (Morteza et al. 2013). However, few studies have carried out a more in-depth analysis of the health risks caused by dust. This paper has therefore made an important in that respect. In addition, compared with traditional evaluation of health risk, the probabilistic risk assessment model based on Monte Carlo method was used to deal with the uncertainty in the evaluation process, making the results more accurate, comprehensive and objective. This paper quantifies the uncertainties and their influence on the health risks of dust, which opens the door for future model building and dust health risk assessment in other areas. Furthermore, compared with the health risk value, the DALY was taken as the quantitative indicator of the dust health damage. This indicator can reflect intuitively the damage caused by dust on the human body and be used to improve the workers' health subsidy.

The research has several important implications for practice. The dust had obviously different health risks on foundry workers in different types of working environments. The evaluation results will help managers to fully understand the dust health impacts on various types of work in the automobile foundry factories and provide scientific basis for the management and decision-making. Sensitivity analysis showed that average time, exposure duration, inhalation rate and dust concentration of various types of work have a considerable influence on the evaluation results. Thus, managers should place more emphasis on these parameters, such as using automation equipment and advanced technology, to reduce the average

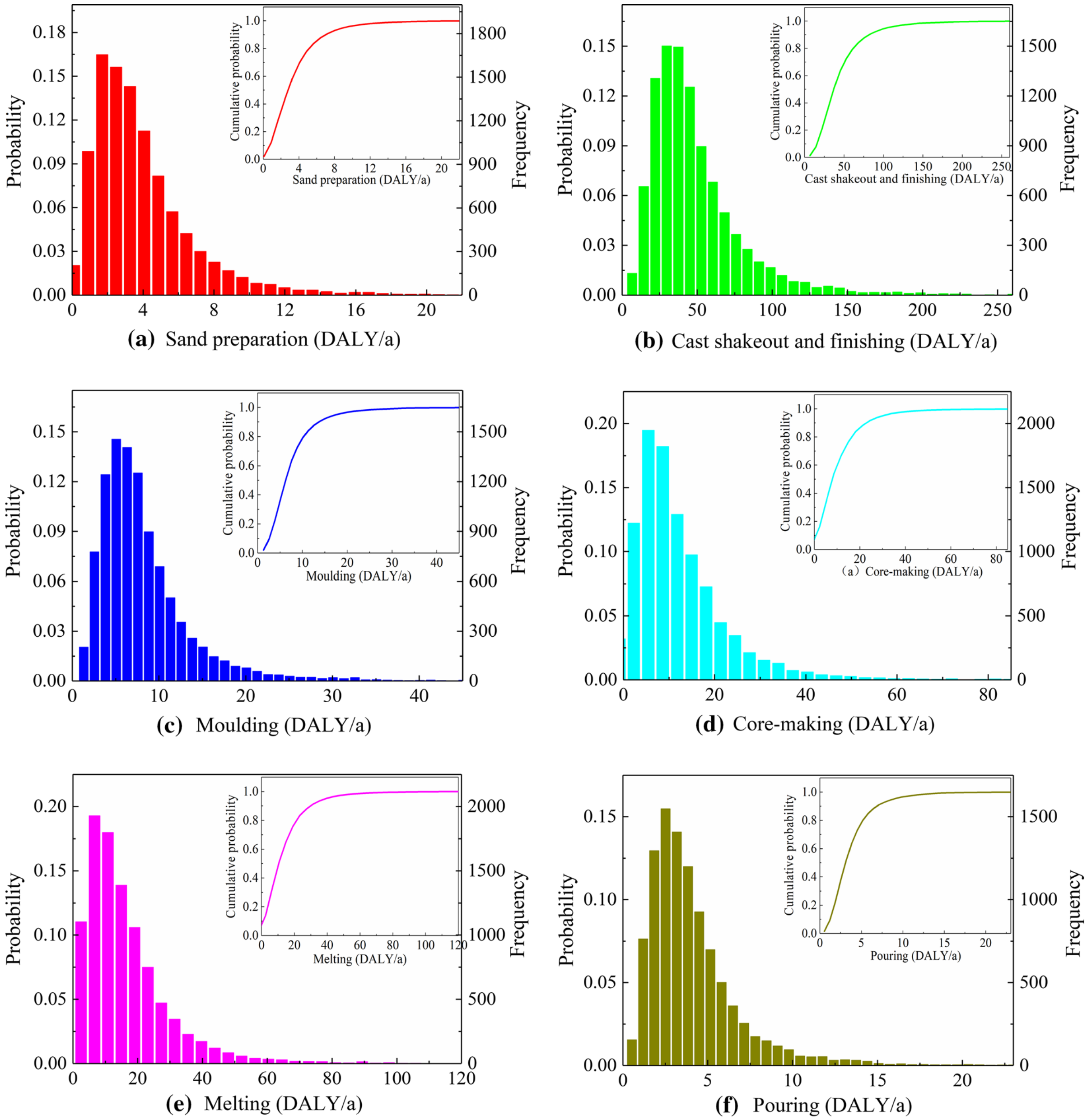

Fig. 7 Health damage of dust for all types of workers

time of workers in the production processes, which would be effective in the mitigation of risks.

Limitations and future research directions

The findings suggest the health risk of dust on various types of work in the automobile foundry factories, which have both theoretical and practical implications. However, there are some limitations when adopting the above evaluation methods for the assessment of dust in foundry industry. Firstly, the value of exposure parameters plays a very important role in health risk assessment. In order to minimize the potential for error, the human body exposure parameters were mainly selected from relevant research conducted within China. Even so, the uncertainty brought about by these exposure parameters cannot be completely eliminated. Additionally, lack of some toxicity values, such as RfD standard value of silica dust, might have a large influence on the risk estimates and make it difficult for regulators to evaluate health risk. Finally, this study only considered inhalation pathway; the health risk value of dust was slightly smaller than the actual value.

Based on these gaps and challenges, future research is recommended as follows:

- The research reported in this paper was undertaken in automobile foundry industry. The major types of work involved are sand preparation, pouring, melting, cast shakeout and finishing, moulding and core-making. It should be encouraged that similar studies can be undertaken in other types of work and in other areas.
- A large-scale investigation and study of exposure parameters should be carried out. In addition, a database of human exposure parameters should be established on the basis of existing research.
- Additionally, dermal contact pathway and ingestion pathway may also contribute to the health risk. Thus, multimedia environmental investigation and further multi-pathway exposure research would be desirable.

Conclusions

The concentration, pollution and health risk assessment of dust on six types of work in an automobile foundry factory were thoroughly investigated in this study. Our findings may provide valuable information for better understanding of dust pollution in foundry, health risks and health damages of workers. The results showed that the mean concentration of dust on six types of work ranged from 1.67 to 5.40 mg/m^3. The health risk level of dust and the influencing factors were evaluated by applying the probabilistic health risk assessment model based on Monte Carlo method. It was concluded that the dust health risks of all types of foundry work follow a lognormal distribution, with melting and cast shakeout and finishing exposed to the greatest risk with $3.84 \times 10^{-6} \pm 3.31 \times 10^{-6}$ and $3.10 \times 10^{-6} \pm 2.02 \times 10^{-6}$, respectively. Cast shakeout and finishing workers, with a DALY of 48.64a, have the most serious dust health damage, followed by melting, core-making, moulding, pouring and sand preparation workers. Sensitivity analysis revealed that the average time, exposure duration, respiration rate and dust concentration of various works have a considerable influence on the evaluation results, with an average effect of − 50.51%, 49.92%, 44.20% and 31.05%, respectively. These findings suggest that using advanced equipment to reduce average time is a promising strategy for mitigating dust health risks to workers.

The presented health risk assessment outcomes and damage values have significant implication from academic and practical perspective. Firstly, in contrast to previous pollution assessments of dust, the probabilistic risk assessment model based on Monte Carlo simulation can characterize the risk assessment results more scientifically and accurately. Secondly, using DALY as the quantitative indicator of the dust health damage intuitively reflects the impairment caused by dust on the human body and be used to improve the workers' health subsidy. Finally, managers are enabled to place more emphasis on influencing variables, such as average time, exposure duration, respiration rate and dust concentration, which offers a new way for managers to control risk in supporting health risk managements of dust in the automobile foundry industry.

However, additional research remains to be carried out to produce a more scientific and comprehensive assessment of the health risk of workers. For example, this study only considers the health risks of dust via inhalation pathway. Dermal contact and ingestion pathway may also contribute to the health risk; thus, further multi-pathway exposure research should be conducted in future studies. In addition, the chemical constituents in dust are commonly found to include metals, PAHs, organic and elemental carbon, and inorganic ions. These chemical substances can be absorbed by human and have adverse effects on the human health. Therefore, health risk assessment of chemical substances in dust will also be the focus of our further research.

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