CONTAMINATION OF THE WORKING AIR VIA METALWORKING FLUIDS AEROSOLS

Erika SUJOVÁ

Abstract: *Utilization of metalworking fluids in the technological process of metalworking brings its advantages and disadvantages, mainly associated with the contamination of the working air through cutting fluid mist. The primary aim of this article is to approximate the mechanism of aerosols generation which contaminates the working air and to draw the attention to the problem of quantification of generated aerosols that are to be kept to exposure limits. The focus has been placed on the mechanisms of cutting fluid mist formation via atomization on a stationary or a rotating workpiece and on the other hand, via vaporization. The next objective is to characterize health risks resulting from the utilization of metalworking fluids in the production process.*

Key words: - metalworking fluid
- aerosol
- health risk

1. INTRODUCTION

Metalworking fluids are complex mixtures used to cool, lubricate, and remove metal chips from tools and metal parts during grinding, cutting, or boring operations. Utilization of metalworking fluids in the technological process of metalworking often generates aerosols by atomization and this mist stream represents a significant hazard to the safety of the workers and to the environment.

The National Institute for Occupational Safety and Health (NIOSH) estimates that 1,2 million employees are exposed to cutting fluids. In order to reduce worker exposure to oil mist, decrease cutting fluid mist control costs, and limit company exposure to environmental regulations and liability, a better understanding of the mechanism of cutting fluid mist formation in the machining process via atomization is required by Yue et al. [1].

There are four types of metalworking fluids: straight oils, soluble oils, semi-synthetics, and synthetics. Most straight oils (also called neat or non-soluble oils) are highly refined products of petroleum stocks, or animal, marine and vegetable oils. Straight oils neither contain nor are diluted with water. Other types of metalworking fluids are water-based mixtures that may require dilution. Metalworking fluids often contain a mixture of other substances including biocides, corrosion inhibitors, metal fines, tramp oils, and biological metalworking fluids is based on the requirements of the task. For example, straight oils are cutting oils and prevent rusting of the metal, while water soluble oils cool and lubricate the metal parts.

This paper is of topical interest for improving the working environment, health and safety of employees in the engineering industry. In the workplace of the author, a scientific grant project SGA SR is currently developed, dealing with the issue.

2. MECHANISMS OF METALWORKING FLUIDS AEROSOLS FORMATION

A prediction study of the amount of produced mist and its corresponding droplet size distribution is a scientific approach to the problem for the following reasons:

- there is a strong relationship between droplet size and droplet suspension,
- the drop size distribution is a key predictor of the concentration of inhalable particles in the workplace and also determines their ability to deposit in various regions of the respiratory systems.

The primary mechanisms through which cutting fluid transforms itself into liquid aerosol in the surroundings are evaporation due to high cutting temperature, spin-off due to the tool or workpiece

rotation, and splash motion associated with the impingement of the fluid jet on the tool, workpiece, or machine, under pressure [2].
During the machining process, impingement of cutting fluid on the workpiece can produce a liquid sheet. The initial disturbances on the liquid film may set up an unbalanced opposition of forces. Surface tension forces oppose the expanding of the sheet and attempt to reinstate the equilibrium, while the aerodynamic forces or centrifugal forces increase the deviation of the sheet and disturb the equilibrium. During its relative motion along the sheet, the air may cause a pressure distribution that increases the amplitude of the disturbances. Disintegration into droplets occurs when the unstable wave amplitude reaches a critical value [1].
These authors also described two kinds of aerosols formation with their mathematic characteristics:

- jet impinging on a stationary workpiece and
- jet impinging on a rotating workpiece.

2.1. The atomization model of jet impinging on a stationary workpiece

One type of machining process consists of a stationary workpiece with a moving tool. In this situation as shown in Figure 1, the cutting fluid jet with radius r_j and velocity V impinges on the flat workpiece at a right angle and a liquid film develops and flows over the flat surface.

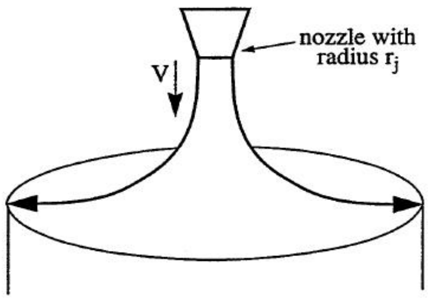

Figure 1. Liquid jet impacting a stationary workpiece [1], a – model situation, b – real situation

The atomization model developed for this process employs the boundary layer equations. For the laminar case, the liquid film velocity profile is approximated using a third order polynomial which results in the following expression for the fluid film thickness as a function of the radial distance along the workpiece,

$$\delta = r_j \left(\frac{1}{2}\left(\frac{r_j}{r}\right) + \frac{3}{8}\sqrt{\frac{280}{39}}(\mathrm{Re}_j)^{-\frac{1}{2}}\left(\frac{r}{r_j}\right) \right)^{\frac{1}{2}} \qquad (1)$$

where:

$$\mathrm{Re}_j = \frac{V_j r_j}{\nu}$$

r – radial distance,
ν - kinematics' viscosity.

The diameter of the droplet is claimed to be nearly proportional to the film thickness t at the point of impingement and can be expressed as $D\alpha\delta^{x}$ [3], where the value of x is between 0,3 and 0,5. For liquids of low viscosity, x is nearly equal to 0,5, while for liquids of high viscosity, the dependence of mean drop size on δ is slightly higher. For the case of a turbulent jet, initial disturbances, primarily caused by turbulent pressure fluctuations, may be strongly amplified as the jet impinges and flows on the stationary workpiece.
The disturbance at the point of impact, ω, scales with the dimensionless group [4]

$$\omega = We_d \exp\left(\frac{0{,}971 l}{d\sqrt{We_d}}\right) \qquad (2)$$

e
between the nozzle and target and d is the liquid jet diameter.
The experimental work by Lienhard (1992) indicates that splattering occurs when ω reaches a value of 2120 irrespective of l/d, and the fraction of the total incoming liquid mass splattered, ξ is given by:

$\xi = -0,0935 + 3,41.10^{-5}.\omega + 2,25.10^{-9}.\omega$

for $2200 \le \omega \le 8500$ (3)

and,

$\xi \le 2,5$ % for $2200 \le \omega \le 3000$ (4)

Additional work will need to be done to determine the droplet size distribution under these conditions.

2.2. The atomization model for a jet impinging on a rotating workpiece

When a cutting fluid jet impacts a workpiece of the radius *R* rotating in the horizontal plane with the angular velocity ω, as shown in Figure 2, three different disintegration models are observed. The three models depending on the fluid flow rate are the drop mode, ligament formation mode and film formation mode.

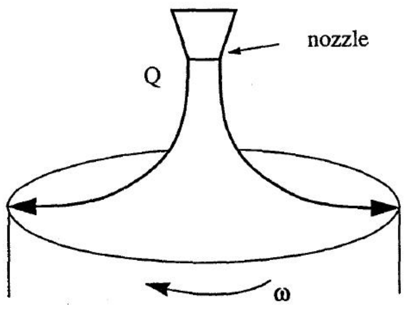

Figure 2. Liquid jet impacting a rotating workpiece

a) Drop mode

For very low cutting fluid flow rate *Q*, a thin fluid film covers the surface of the workpiece. The drops separate from the edge of the surface when the centrifugal force exceeds the force due to surface tension γ. The equilibrium of these forces is given by:

$$\frac{\pi D^3}{6}\rho R\omega^2 = \pi D\gamma \quad (5)$$

where: ρ is fluid density.

Solving for the drop diameter *D*

$$D = \frac{c}{\omega}\left(\frac{\gamma}{\rho.R}\right)^{\frac{1}{2}} \quad (6)$$

where theoretically $c = \sqrt{6}$, which is given by (5). Since at the time of droplet formation, the centrifugal force may actually exceed the surface tension force, the actual value of c is not expected to equal $\sqrt{6}$. Disturbances in the process lead to a distribution of drop diameters. Large drops along with numerous small satellite droplets are observed as depicted in Figure 3.

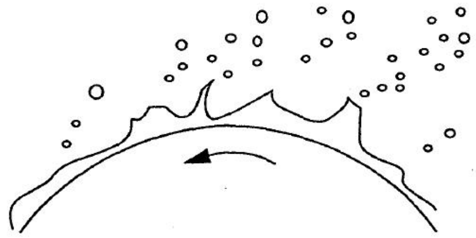

Figure 3. Drop formation mode [1]

b) Ligament formation mode

As the cutting fluid flow rate increases up to a certain limiting value, the film experiences wave disturbances. Many unstable liquid ligaments appear at the circumference and break up into small drops of varying size as is shown in Figure 4. The trajectory of a ligament which develops at the edge is described by the following approximate system of equations [5]:

$$x = R\cos(\omega t) + R\omega t\sin(\omega t) \quad (7)$$

$$y = R\sin(\omega t) - R\omega t\cos(\omega t) \quad (8)$$

The ligament diameter d_l can be determined from empirical relations as:

$$d_l = c'R\left(\left(\frac{1}{N_l}\right)^{\frac{2}{7}}\left(\frac{\gamma}{\rho R^3\omega^2}\right)^{\frac{2}{7}}\left(\frac{\rho Q^2}{R^3\gamma}\right)^{\frac{1}{7}}\right) \quad (9)$$

where N_l is the number of ligaments, and c' is an experimentally determined constant.

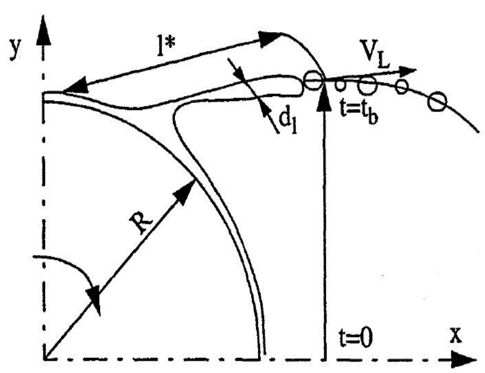

Figure 4. Ligament formation modes

According to the Weber theory, the drop diameter is approximately, as Kang [6] described in his work

$$D = \left(\frac{3\pi}{\sqrt{2}}\right)^{\frac{1}{3}} d_1 \left[1 + \frac{3\mu}{(\rho\gamma d_1)^{\frac{1}{2}}}\right]^{\frac{1}{6}} \qquad (10)$$

The drop diameter obtained by substituting Eq. (9) into Eq. (10) compares favourably with the empirical equation for drop diameter (cm) [1] (11):

$$D = 5{,}75 N^{-0{,}79} \cdot Q^{0{,}32} \cdot R^{-0{,}69} \cdot \rho^{-0{,}29} \cdot \gamma^{0{,}26} (1 + 0{,}23\mu)^{0{,}65}$$

where, N is the rotational speed and μ is the dynamic viscosity. The units of $D, Q, R, \rho, \gamma, \mu$ are cm, $cm^3.s^{-1}$, $g.cm^{-3}$, $g.s^{-2}$ and $g.cm^{-1}.s^{-1}$ respectively.

c) Film formation mode

At high flow rates and high rotation speed, the ambient medium causes strong disturbances and the liquid film directly disintegrates into drops.

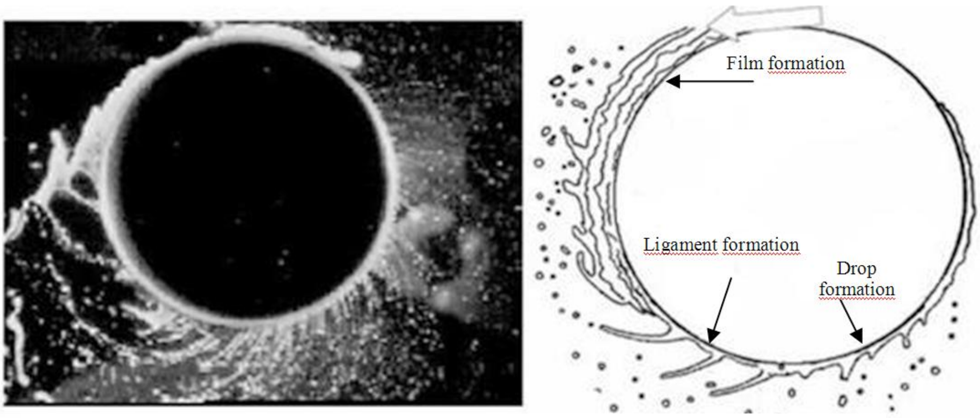

Figure 5. Three different disintegrations modes [7]

The machining process does not normally operate under these conditions. Dado et al. [7] presented three different disintegrations modes, as is illustrated in Figure 5.

d) Preventing possibilities for real machining

There are different approaches to prevent the generation of aerosols. The proper design and operation of the metalworking fluid system include minimizing fluid delivery pressure, matching the fluid to the application, using metalworking fluid formulations with low oil concentrations, avoiding contamination with tramp oils, minimizing the fluid flow rate, covering fluid reservoirs and return systems where possible, and maintaining control of the fluid chemistry. The other method for reducing aerosol generation is a chemical treatment which includes chemicals to modify the properties of the fluid so as to reduce its potential for forming a stable aerosol. Most of the anti-mist polymers are polyisobutylene, polyethylene oxide or associative polymers. The former polymer class can be used in straight oil systems, while the latter two are suitable for water-dilatable fluids. However, the physical theory behind mist suppressants is based on the atomization mechanism of mist formation, and, as a result, such methods may have little effect on reducing mist practices generated via vaporization/condensation [8].

3.HEALTH RISKS OF THE UTILIZATION OF METALWORKING FLUIDS

Metalworking fluids can cause adverse health effects through skin contact with contaminated materials, spray, or mist and through inhalation from breathing mist or aerosol.

Skin and airborne exposures to metalworking fluids have been implicated in health problems including irritation of the skin, lungs, eyes, nose and throat. Conditions such as dermatitis, acne, asthma, hypersensitivity pneumonitis, irritation of the upper respiratory tract, and a variety of cancers have been associated with exposure to metalworking fluids. The severity of health problems is dependent on a variety of factors such as the kind of fluid, the degree and type of contamination, and the level and duration of the exposure [8].

3.1. Skin Disorders

Skin contact occurs when the worker dips his/her hands into the fluid or handles parts, tools, and equipment covered with fluid without using personal protective equipment, such as gloves and aprons. Skin contact may also result from fluid splashing onto the employee from the machine if guarding is absent or inadequate.

Two types of skin disease associated with metalworking fluids exposure are contact dermatitis and acne.

The two kinds of contact dermatitis are irritant contact dermatitis and allergic contact dermatitis. In irritant contact dermatitis, the rash is confined to the area in contact with the irritating substance. In allergic contact dermatitis, the rash can spread beyond the area directly in contact with the irritant.

Straight oils are often associated with acne-like disorders characterized by pimples in areas of contact with the metalworking fluids. Red bumps with yellow pustules may develop on the face, forearms, thighs, legs, and other body parts contacting oil-soaked clothing.

3.2. Respiratory Diseases

Inhalation of metalworking fluids mist or aerosol may cause irritation of the lungs, throat, and nose. In general, respiratory irritation involves some type of chemical interaction between the metalworking fluids and the human respiratory system. Irritation may affect one or more of the following areas: the nose, throat (pharynx, larynx), the various conducting airways or tubes of the lungs (trachea, bronchi, bronchioles), and the lung air sacks (alveoli) where the air passes from the lungs into the body. Human exposure to metalworking fluids mist or aerosol may also aggravate the effects of existing lung disease.

Also, high exposures to metalworking fluids have been associated with asthma. A variety of components, additives, and contaminants of metalworking fluids can induce new-onset asthma, aggravate pre-existing asthma, and irritate the airways of non-asthmatic employees.

Chronic bronchitis is a condition involving inflammation of the main airways of the lungs that occurs over a long period of time. Chronic bronchitis is characterized by a chronic cough and by coughing up phlegm. The phlegm can interfere with air passage into and out of the lungs. This condition may also cause accelerated decline in lung function, which can ultimately result in heart and lung function damage.

Other factors, such as smoking, increase the possibility of respiratory diseases. Cigarette smoke may worsen the respiratory effects of metalworking fluids aerosols for all employees.

3.3 Cancer

A number of studies have found an interplay between working with metalworking fluids and a variety of cancers, including cancer of the rectum, pancreas, larynx, skin, scrotum, and bladder. Studies of metalworking fluids and cancer have relied on the health experiences of workers exposed decades earlier. This is because the effects of cancers associated with metalworking fluids may not become evident until many years after the exposure. Airborne concentrations of metalworking fluids were known to be much higher in the 1970s - 80s than those today. The composition of metalworking fluids has also changed dramatically over the years. The fluids in use prior to 1985 may have contained nitrite, mildly refined petroleum oils, and other chemicals that were removed after 1985 for health concerns. Based on the substantial changes that have been made in the metalworking industry over the last decades, the cancer risks have likely been reduced, but there is not enough data to prove this [9].

4. DISCUSSION AND CONCLUSION

Metalworking fluid mist exposure in workplace atmospheres have generally been assessed using one of three methods: integrated monitoring for total particulates, integrated monitoring for metalworking fluid mist specific components, and direct-reading monitoring for either total aerosols or size-selective fractions of the aerosols [10, 11].

The assessment of occupational health risks caused by airborne metalworking fluid emissions is either based on the sum of aerosols and vapour or on aerosols solely. The inhalation hazards of metalworking fluid mist are caused by exposure to three agents: neat fluid, microbial contaminants, and other chemical contaminants of the fluids. The neat fluid comprises chemical agents, some of which have existing occupational exposure limits, such as mineral oil, ethanolamine, and diethanolamine. Various techniques are used to determine the weight of oil mists collected on the filters: gravimetry, spectrophotometry using ultraviolet wavelength or infrared spectrophotometry. However, with all these methods, evaporation can occur from oil mist droplets collected on filter membranes, because the droplets remain in contact with flowing air during sampling [12, 13]. Assessment of the hazards due to bio-contaminants released by metalworking fluids requires sampling techniques that, on the one hand, provide a high collection efficiency of airborne microorganisms, and, on the other hand, allow optimum recovery of the collected microbial particles with minimum death or injury to the organisms.

In connection with the above theory of fluid mist formation, we can suggest following options for operator's protection or for reducing exposure to metalworking fluid mist:

1. pollution prevention - preventing metalworking fluids mist generation,
2. pollution control - reducing exposure by the application of a number of well-known principles including engineering and work practice controls, administrative controls, and use of personal protective equipment [11].

Ad 1: We can prevent mist generation via: minimizing fluid delivery pressure, matching the fluid to the application, using metalworking fluid formulations with low oil concentrations, avoiding contamination with tramp oils, minimizing the fluid flow rate, covering fluid reservoirs and return systems where possible, and maintaining control of the fluid chemistry or using of chemical treatment.

Ad 2: We can reducing exposure by:

- Engineering controls: to add a machine enclosures (total or tunnel), to install an exhaust ventilation system, to design an original equipment manufacturer (OEM) enclosures with local exhaust ventilation or to install a mist collectors whose collection mechanism of centrifugal separators is based on centrifugal impaction or on electrostatic precipitators.

- Administrative controls: include job rotation, good personal hygiene and proper housekeeping practice. Very important is also training employees to follow the proper work practices and operational procedures for their jobs.

The different mechanisms by which atomization occurs in various machining conditions were presented along with some simple models to predict droplet size and mass of splattering. The following research work will emphasize the refinement of existing models as well as the development of new models with the use of experimental data for verification. An objective of this modelling activity will be to predict the character of the mist droplets including the amount of mist formed, the droplet size distribution, and droplet chemical composition.

5. LIST OF SYMBOLS

radius	r_j	rad
velocity	V	$cm.s^{-1}$
radial distance	r	rad
kinematical viscosity	ν	$cm^2.s^{-1}$
Reynolds number	Re	
angular velocity	ω	$rad.s^{-1}$
Weber number	We	
distance	l	cm
liquid jet diameter	d	cm
surface tension	γ ,	$g.s^{-1}$
fluid density	ρ ,	$g.cm^{-3}$
drop diameter	D,	cm
ligament diameter	$d_{l,}$	cm
rotational speed	N,	$cm.s^{-1}$
dynamic viscosity	μ ,	$g.cm^{-1}.s^{-1}$

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Author's address:
MSc. Erika Sujová, PhD.
Technical university in Zvolen, Faculty of environmental and manufacturing technology, Department of manufacturing technology and materials,
Študentská 26, 960 53 Zvolen,
Slovak republic.
e-mail: esujova@vsld.tuzvo.sk,
sujovae@gmail.com