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Investigation of the efficiency of the lateral exhaust hood enhanced by aeroacoustic air flow

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ABSTRACT

This paper presents a novel concept of local push-pull ventilation system used to remove aerosol particles from open surface tanks. Sound waves generated by aerodynamic sound generator are introduced into the push air flow of lateral exhaust hood and used to agglomerate aerosol particles. Results of calculation of parameters of sound generator and aeroacoustic air flow are presented. It is established that 5–10 μm aerosol particles are aggregated better at frequencies below the ultrasonic range (1–5 kHz) and aerosols with a particle size of less than 5 μm are more effectively aggregated at ultrasonic frequencies. It was experimentally established that the relative air humidity measured above open surface tank is decreased up to 1.6 times in presence of acoustic field as compared with humidity obtained for conventional push-pull air removal system. It is also obtained that increase of the temperature of the liquid increases the aerosol removal efficiency of lateral exhaust hood enhanced by aeroacoustic air flow.

1. Introduction

Electroplating is widely used in various industries such as automobile, electronic, jewellery, etc. This process allows manufacturers to use inexpensive metals such as steel or zinc for the majority of the product and then apply different metals on the outside to improve the surface properties (Li et al., 2015) of the product (such as wear resistance, lubricity, corrosion resistance, aesthetic look, etc.). However, electroplating processes are accompanied by gas and aerosol emissions. Gases which are formed during the electroplating process evolve as small gas bubbles at the metal surfaces of the anode and cathode electrodes (Pilat and Pegnam, 2006). When these small bubbles rise to the liquid solution surface and burst, aerosol droplets are formed (Pilat and Pegnam, 2006). This results in the release of various hazardous substances (like chromic acid).

The impact of aerosols on human health mainly depends on their physical and chemical properties, particle size and shape, concentration in the air and exposure time. The most dangerous are aerosol particles of about 5 μm in size, because they are able to penetrate deep into the lungs (Scholl et al., 1999). Particles with aerodynamic diameter $AD > 15$ μm are effectively filtered by the upper respiratory tract. Particles with $AD < 10$ μm differentially deposit in the upper respiratory tract (Scholl et al., 1999). With the rise of the working environment temperature, risk of poisoning increases, because volatility and evaporation rate of materials increase with increase of the temperature. An increase in air humidity can also result in increase of toxicity of some materials like hydrochloric acid and hydrogen fluoride. Therefore, prevention and control of air pollution are extremely important in electroplating and other processes which are characterized by vapour and aerosol formation.

Most of the mechanical equipment used to remove the hazardous aerosols from open surface tanks is not effective. Usually lateral exhaust hoods are used to remove harmful pollutants. However, their performance predicted using computational methods is often not achieved in practice, because it depends on the mass transfer processes occurring above the surface of the liquid. The main drawback of the lateral exhaust system is that the air velocity decreases rapidly with distance from the exhaust channel, and very large exhaust flow rates are necessary for a large tank to capture the pollutants evaporated from the surface of the tank farthest from the exhaust channel (Chern

Abbreviations: AD, aerodynamic diameter; IR, infrared; PC, personal computer.

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Nomenclature

a_1	Distance from the nozzle to the beginning of the instability zone
b_1	Distance to the end of the instability zone
C	Mass concentration of monodisperse particles
c	Speed of sound
D	Diameter of the resonator sphere
d	Diameter of the nozzle
d_p	Particle diameter
f	Frequency of acoustic waves
K_a	Dimensionless coagulation coefficient which depends on sound intensity
k	Integer number
L	Length of the resonator
L_m	Distance between aerosol particles after the time t
L_{m0}	Initial distance between aerosol particles distributed in the air
M_i	Molecular mass of the component
M_m	Relative molecular mass of the medium
n_0	Initial number concentration of aerosol particles in 1 cm^3 of air
n	Number concentration of aerosol particles in 1 cm^3 of air after the time t
p	Environmental pressure
p_i	Partial pressure of the component in mixture at the temperature T_{lq}
p_0	Compressed air pressure
r_p	Radius of aerosol particle
r_{p0}	Initial radius of aerosol particle
S	Distance from the resonator to nozzle
Sat	Sutherland's constant
T_{lq}	Temperature of the liquid
t	Time
u_m	Oscillation velocity of the medium
u_p	Oscillation velocity of the particle
x_m	Oscillation amplitude of the medium
x_p	Oscillation amplitude of the particle

Greek letters

δ	Relative air humidity
η_p	Particle entrainment coefficient
λ	Coefficient
μ_i	Dynamic viscosity coefficient of the component in mixture at the temperature T_{lq}
μ_m	Dynamic viscosity coefficient of the medium
μ_0	Dynamic viscosity coefficient of the component at the temperature 0 °C
ρ_m	Density of the medium
ρ_p	Particle density
τ	Particle relaxation time
φ	Phase shift between oscillations of the medium and the particle
ω	Angular frequency

Subscripts

i	Component index

and Ma, 2007). In order to reduce the concentration of hazardous substances in the air breathed by workers it is necessary to develop new interdisciplinary removal technologies.

Complex processes occur above hot liquid surface during the work of lateral exhaust hood. Under the action of lift forces aerosol particles rise to the top and lateral hood attached to the edge of the tank should be able to maintain such velocity of air flow that would force the particles to change their direction of movement by 90°. When exhaust hood does not work or the velocity of the air flow is not enough, aerosol particles in the opposite side of the hood are not sucked into it.

Many researchers have worked on improving the efficiency of aerosol removal equipment. Pull hoods combined with push air flows are one of the simplest solutions that have been widely applied in the industries that require the removal of contaminant vapours, fumes or aerosols from a large open surface (Huang et al., 2005). It is reported that a push-pull system can save air flow by about 50% when compared with using lateral exhaust hood alone (Huang et al., 2005; Rota et al., 2001).

The push–pull systems involve an air flow that is blown from one side of the tank and collected by an exhaust hood on the opposite side (Rota et al., 2001). The push–pull ventilation systems have complex flow dynamics (Flynn et al., 1995; Robinson and Ingham, 1996; Rota et al., 2001), where the push flow behaves in accordance with four mechanisms (Marzal et al., 2003): (a) formation of the initial curtain or semi-free jets; (b) formation of the transition flow in the impact zone denominated wall jet reorganization; (c) formation of the wall jet that enters over the tank surface and forms vortices against the side walls; and (d) entrance into the exhaust hood.

Due to the complexity, most of the recommended push–pull ventilation system design guidelines in the literature were based on the experimental results of tracer gas concentration measurements together with empirical rules for tuneable parameters (Huang et al., 2005). They give recommendations for a restricted range of operating and environmental conditions. Although useful, these guidelines do not allow for predicting either the concentration of pollutant close to the open tank or the influence of several important operating parameters, such as airflow rates (both blowing and exhaust), geometry of the tank, and room air currents (Rota et al., 2001). In particular, there is no a general agreement on how to deal with two very important variables, crossdraft velocity and width of the tank (Rota et al., 2001). There is still need for more study in the flow physics that governs the transport process of the contaminants, the push flows and the environmental air through the pull hood, and design strategy based on the flow physics is also a field where more effort is required (Huang et al., 2005).

Reduction of the concentration of aerosols can be achieved by generation of the sound waves over the pollution source. In other words, the acoustic agglomeration process can be involved in the aerosol removal process. Acoustic agglomeration is a process in which high intensity sound waves produce relative motions of particles suspended in gaseous media (Zhou et al., 2015; Zhang et al., 2012; Vekteris et al., 2014, 2015). These motions cause collisions between particles in which they merge together and form larger structures or agglomerates. These agglomerates continue to connect with each other, become larger and heavier and then fall down under the action of weight forces. Gravitational agglomeration follows the acoustical (Spurny, 2000).

Ability to integrate the sound generator into the aerosol removal process and reduction of the amount of transported aerosol particles is the difficult challenge. This task can only be solved with deep understanding of aeroacoustic flow physics, after thorough studies of acoustic field effects on aerosol particles, results of which would justify the development of these aerosol removal systems and allow to develop experimental research methodology. Although the sufficient progress in the research of the influence of acoustic field on aerosol agglomeration is achieved, such phenomena and processes are too complex and it is too difficult or almost impossible to adapt such research achievements for practical use. Therefore, creation and development of these systems should be based on the research works carried out in a specific work environment. One of the main design goals for such systems is achievement of maximum suction, blowing and acoustic field generation efficiency in the same removal equipment.