Analysis of the Hazards for the Molten Cuprous Chloride Pouring Operation in an Industrial Hydrogen Production Facility

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ABSTRACT
An analysis is reported of a design for a local exhaust ventilation system for the molten CuCl pouring station in an industrial plant. Heat recovery from molten CuCl is a key process within the copper-chlorine (Cu-Cl) cycle of thermochemical water splitting for hydrogen production. Due to particulate matter, dust, and vapours emitted by the molten salt, an effective and safe HVAC design is crucial. The design process involves calculating duct diameters to provide the desired duct air velocity through the system. The static pressure is evaluated so that the fan size can be determined. An adequate supply of make-up air must be provided to replace the air exhausted through the ventilation system. The economics of the ventilation system and ways to protect employee health, as well as minimize the costs associated with exhaust ventilation, are also described.

Keywords: hydrogen production, Cu-Cl thermochemical cycle, cuprous chloride hazards, industrial ventilation

1. INTRODUCTION

Hydrogen is widely believed to be the world's next-generation fuel, since its oxidation does not emit greenhouse gases that contribute to climate change. To be sustainable, a hydrogen production process must be driven by forms of energy produced without greenhouse gas emissions. Over 200 cycles have been identified previously to produce hydrogen by thermochemical water decomposition from various heat sources, including nuclear and solar energy [1]. The copper-chlorine (Cu-Cl) cycle is a potential future cycle that could be linked with nuclear reactors, or other heat sources such as solar energy, to thermally decompose water into oxygen and hydrogen, through intermediate copper and chlorine compounds.

The hazards accompanying the copper-chlorine cycle have rarely been reported, although they are important to industrialization of the technology. As the output of the cycle only consists of hydrogen and oxygen, the main hazards are generated from internal intermediate compounds that are recycled within the Cu-Cl cycle. It is important to predict, control and reduce the hazards caused by the intermediate chemicals. Cuprous chloride (CuCl) is an intermediate compound that is always present in the Cu-Cl cycle regardless of the variations of the cycle. Cuprous chloride can cause various health impacts [2]. It can cause irritation to the respiratory tract, and can lead to such symptoms as coughing, sore throat, and shortness of breath. When heated, this compound may release copper fumes, which can cause symptoms similar to the common cold, including chills and stuffiness of the head. The compound can also cause irritation, redness, and pain if contacted with the skin or eyes, and can cause some individuals to develop copper allergies. Prolonged or repeated skin exposure may cause dermatitis. Prolonged or repeated exposure to dusts of copper salts may cause discoloration of the skin or hair, blood and liver damage, ulceration and perforation of the nasal septum, runny nose, metallic taste, and atrophic changes and irritation of the mucous membranes.

The processing of CuCl in the cycle includes heat recovery, solidification, granulation, and dissolution. The overall efficiency of the cycle can be improved by recovering as much heat as reasonably feasible within the cycle and minimizing the net heat supply to the cycle. Up to 87% of the total heat recovery within the Cu-Cl cycle can be recovered from molten cuprous chloride [3]. A direct contact heat exchanger for recovering heat from molten CuCl was proposed by Jaber et al. [4] who evaluated the convective heat transfer from molten CuCl droplets in a counter-current spray flow. A comparative review of different options for recovering heat from molten CuCl was presented by Ghandehariun et al. [5]. It was shown that rotary/spinning atomization, atomization and steam generation with a separate vessel, and casting/extrusion methods may be the most effective methods for heat recovery from molten CuCl. However, past studies of the heat recovery focused on the thermal efficiency of various methods and have not addressed the potential hazards.

Pouring molten CuCl into the heat recovery chamber generates a cloud of fumes which is toxic and hazardous to workers. This paper describes the fundamentals of a preliminary system design for the molten CuCl pouring operation in an industrial facility, and the use of air cleaning devices to remove contaminants before discharge to the outdoor air. The primary function of an industrial ventilation (IV) system is to prevent employee over-exposure to airborne contaminants generated in the workplace. Insufficient ventilation may be manifested by worker complaints or obvious eye, nose or throat irritation upon entering the work environment. Air sampling may be necessary to evaluate exposure conditions, especially where substances with poor warning properties are in use. A properly functioning IV system helps maintain a safe and comfortable work environment, as well as prolonging the life of corrosion-susceptible plant components and equipment.

2. BACKGROUND

With recognition that the concentration field in a room, especially near the contaminant source, is not uniform, improvements in air quality have been proposed by several researchers [6-9]. Sherman et al. [10] discuss and use tracer gas techniques to measure ventilation in a single zone. An improvement on these models was achieved by the uniform diffusivity model [11]. This model assumes that the contaminant transport away from the source is due to turbulent diffusion, and the intermingling and mixing of parcels of air, resulting in a net movement of the contaminant from high to low concentration regions. A typical formulation of this model for isentropic diffusion from a point source on a flat surface is derived by analogy with heat transfer [11].

Khan et al. [12] investigate several inlet and exhaust locations and types to determine the optimum inlet and exhaust positions. Average contaminant concentrations are calculated for the entire room, the breathing zone plane, and the near-source breathing zone.

The concepts of accessibility of supplied air (ASA) and accessibility of contaminant source (ACS) are introduced by Yang et al. [13] to quantify the contribution of supply inlets and indoor sources on the transient contaminant dispersion in the space. Under emergency conditions, the application of this method helps to choose a flexible ventilation mode and to implement intelligent controls to meet various requirements.

The ventilation efficiency of an indoor environment under various inlet/outlet arrangements is investigated by Chung and Hsu [14] using numerical analysis and experimental validation. The results show that the air exchange rate is influenced by the air supply volume, and it is insensitive to the locations of inlet/outlet diffusers. The location of inlet and outlet diffusers significantly influences the ventilation efficiency.

Budaiwi [15] uses an air flow model in conjunction with an indoor air quality (IAQ) model to investigate contaminant concentration in a single zone enclosure under combined dilution and pressurisation effects of ventilation air. The air flow model takes into account all relevant processes determining contaminant concentration, but assumes a non-active absorption/desorption process and a filtration process independent of contaminant characteristics and air flow rate.

The technical and economic performances of mixing and hybrid displacement ventilation systems for cooling large industrial buildings are compared by Caputo and Pelagagge [16]. The comparison is carried out by resorting to a systematic methodology including smoke tracer experiments and temperature measurements on the existing mixing ventilation plant, and a pilot plant test incorporating a single displacement diffuser.

Rohdin and Moshfegh [17] examine energy use and the thermal climate in a large Swedish light alloy foundry by means of energy simulation, CFD and measurements. The technical potential for using variable air volume (VAV) systems is investigated using these methods.

3. THERMOCHEMICAL COPPER-CHLORINE CYCLE FOR HYDROGEN PRODUCTION

The copper-chlorine (Cu-Cl) cycle is a highly promising cycle for producing hydrogen thermochemically. This method has been investigated by Atomic Energy of Canada Ltd. (AECL) at its Chalk River Laboratories. Intermediate Cu-Cl compounds are utilized to decompose water into hydrogen and oxygen [18]. A set of reactions are utilized in the Cu-Cl thermochemical cycle in order to obtain the overall water splitting into oxygen and hydrogen:

$$H_2O\ (g) \rightarrow H_2 + 1/2O_2 \quad (1)$$

A possible realization of the Cu-Cl cycle is shown in Fig. 1. Two variations of the Cu-Cl cycle are under investigation: 5-step and 4-step. In the 5-step cycle, aqueous cupric chloride is dried to solid cupric chloride particles, and fed to the hydrolysis reactor to produce copper oxychloride. The 4-step cycle combines these processes by supplying cupric chloride to the hydrolysis chamber, by means of a fluidized bed or nebulizer to produce the solid copper oxychloride. The 4-step cycle has an advantage of reducing complexity by eliminating solids handling and thus requiring less equipment.

Cuprous chloride (CuCl) exits a copper oxychloride decomposer, cools, solidifies, dissolves in aqueous HCl, and then produces hydrogen via the following electrochemical reaction:

$$2CuCl(aq)+2HCl(aq) \rightarrow H_2(g)+2CuCl_2(aq) \quad (2)$$

In the second step of the Cu-Cl cycle, the aqueous $CuCl_2$ from the electrochemical cell enters the flash dryer for solid $CuCl_2$(s) production. A drying medium such as air is necessary for step 3 in which the device must provide adequate heat to dry the mixture and generate solid $CuCl_2$. In step 3, HCl (g) and $CuO*CuCl_2$ are produced at 430ºC in a fluidized bed reactor, through the following reaction:

$$2CuCl_2(s) + H_2O\ (g) \rightarrow CuO*CuCl_2(s) + 2HCl\ (g)$$
(3)

Solid $CuCl_2$ particles and high temperature steam mix in this step to produce the two exit streams. Steam enters a bed of $CuCl_2$(s) particles that is provided by step 2. Then $CuO*CuCl_2$ solid particles and HCl (g) exit the reactor. The HCl (g) is provided to the hydrogen production step (step 1). The solid particles are supplied to the reactor for oxygen production (step 4), where the copper oxychloride reaction occurs:

$$CuO*CuCl_2(s) \rightarrow 2CuCl\ (l) + ½\ O_2\ (g) \quad (4)$$

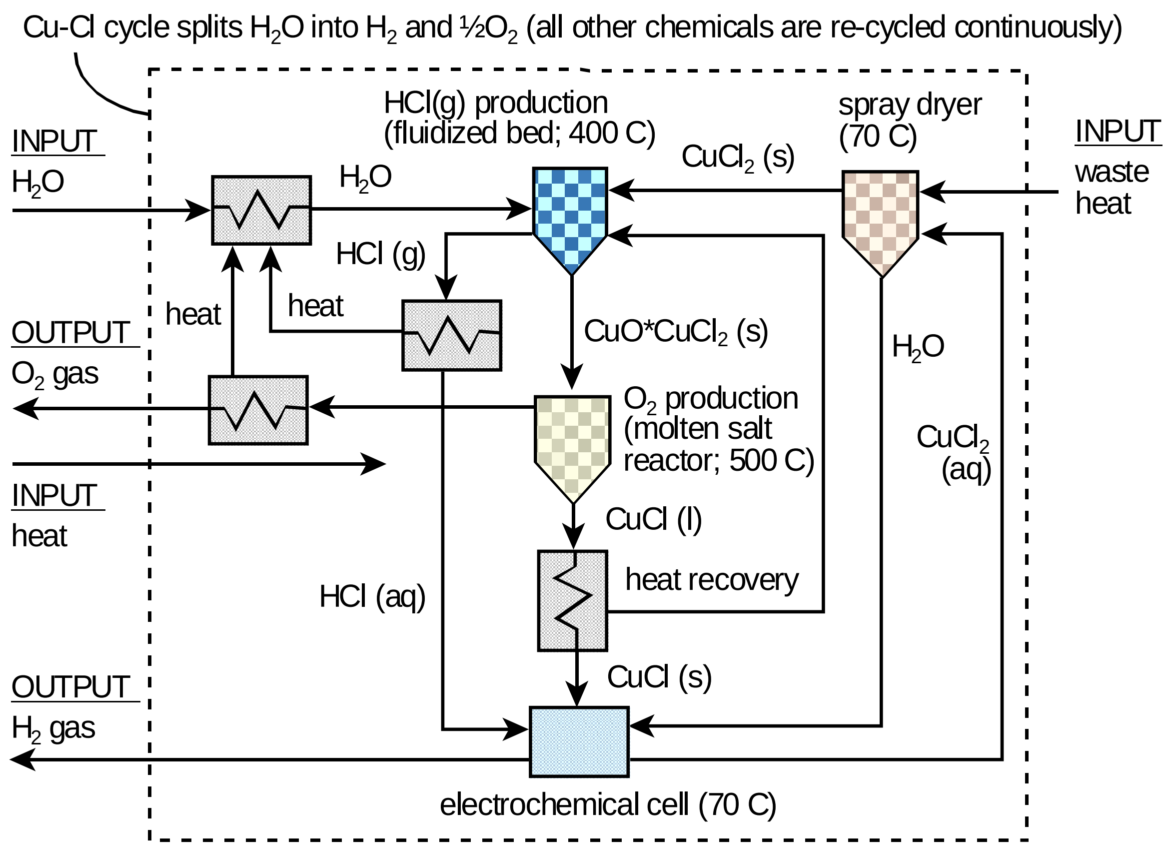

Fig. 1 Schematic of the copper-chlorine (Cu-Cl) cycle

4. TYPES OF VENTILATION SYSTEMS

4.1 Dilution Ventilation

Dilution occurs when contaminants released into the work room mix with air flowing through the room (Fig. 2). Either natural or mechanically-induced air movement can be used to dilute contaminants [19]. The major disadvantages of dilution ventilation are that large volumes of dilution air may be needed. Also, employee exposures are difficult to control near the contaminant source where dilution has not yet occurred.

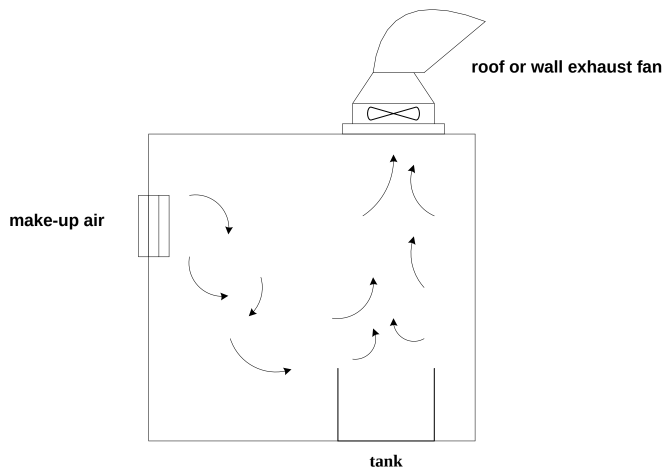

Fig. 2 Dilution ventilation

4.2 Local Exhaust Ventilation

Local exhaust systems capture and contain contaminants at their source before they escape into the workplace (see Fig. 3). A typical system consists of ducts, hoods, an air cleaner, and a fan. The main advantages of local exhaust systems are that they remove rather than dilute contaminants, and they require less air flow than dilution ventilation systems in the same applications. The total air flow is important for plants that are heated or cooled since heating and air conditioning costs are an important operating expense [19].

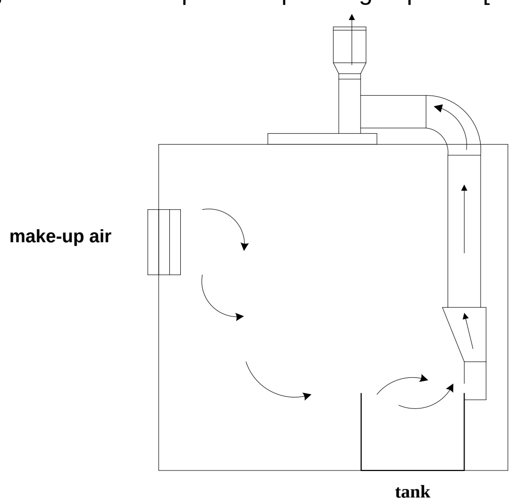

Fig. 3 Local exhaust ventilation

4.3 Contaminant Characteristics

Vapours and fumes do not exhibit significant inertial effects and move with the air in which they are mixed. The hood needs to generate an air flow pattern and capture velocity that are sufficient to control the motion of the contaminant-laden air, plus extraneous air currents caused by room cross-drafts, etc. Fumes and vapours are airborne, moving with air currents and not subject to appreciable upward or downward motion due to their densities. Normal air movement assures mixing of these contaminants in air. As air flows around an object, boundary layer separation occurs. The wake is a region of vigorous mixing and recirculation. If the object is a person working with, or close to, a contaminant source, recirculation of the contaminant into the breathing zone is likely. Important design considerations for ventilation contaminant control are minimizing the wake around people, and keeping contaminant sources out of recirculating regions [20].

5. DESIGN PROCEDURE

The present exhaust system design begins with the individual exhaust hood, which draws emissions from the tank surface and away from the workers' breathing zone, preferably in an energy-efficient manner. The exhaust flow and energy required depends on the process and the degree to which it can be physically enclosed. After hood configuration selection, the next design step is to calculate the required exhaust flow, based on the operation and its size, temperature, contaminant types and their rate of evolution. In general, exhaust flows should adequately control workroom air concentrations to within acceptable health levels.

5.1 Hood Types and Design Factors

Hoods can be grouped into enclosing and exterior categories. The appropriate type of hood depends on the physical characteristics of the process equipment, the contaminant generation mechanism, and the operator interface. Enclosing hoods completely or partially enclose the process or contaminant generation point. An inward flow of air through the enclosure opening contains the contaminant within the enclosure and prevents its escape into the work environment. Exterior hoods are located adjacent to an emission source without enclosing it. A variation of the exterior hood is the push-pull system, in which a jet of air is pushed across a contaminant source into the flow field of a hood. Contaminant control is primarily achieved by the jet, which is received and removed by the exhaust hood. An enclosing hood is preferred when the process configuration and operation permit, and the maximum possible partial enclosure should be used if complete enclosure is not feasible.

Capture and control of contaminants are achieved by the inward air flow created by the exhaust hood. Air flow toward the hood opening must be sufficiently high to maintain control of the contaminant until it reaches the hood. External air motion may disturb the hood-induced air flow and require higher air flow rates to overcome the disturbing effects. Elimination of sources of external air motion is an important factor in achieving effective control without the need for excessive air flow and its cost. The hood-induced air velocity necessary to capture and convey the contaminant into the hood is dependent on the hood air flow rate and configuration. For round and rectangular hoods which are roughly square, the air flow rate can be approximated by [21]:

$$Q = 45 \times 10^5 \times V(10X^2 + A) \quad (5)$$

Here, Q is air flow rate ($m^3\ s^{-1}$), V is centerline velocity ($m\ s^{-1}$) at a distance X from the hood, and A is area (m^2) of the hood opening (see Fig. 4). Also, X is distance outward along axis and should be within 1.5D, where D is the diameter of round hoods or side length of essentially square hoods.

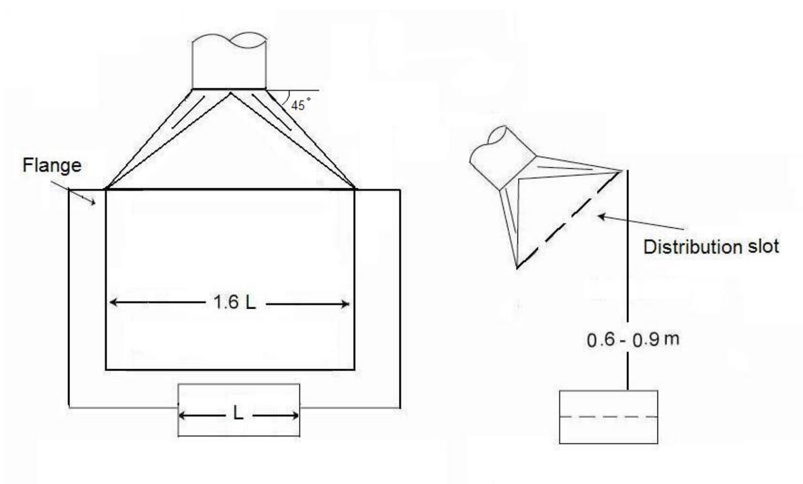

Fig. 4 Molten CuCl pouring station

5.2 Hood Losses

As air enters the duct, a vena contracta is formed and a small energy loss occurs first in the conversion of static pressure to velocity head. As the air passes through the vena contracta, the flow area enlarges to fill the duct and velocity head converts to static pressure. The uncontrolled slowing of the air from the vena contracta to the downstream duct velocity results in the major portion of the entry loss. The more pronounced the vena contracta, the greater is the energy loss and hood static pressure.

The overall hood entry loss h_e can be expressed in terms of hood loss coefficients and the slot or duct velocity pressure. The hood static pressure *SP* is the hood entry loss plus the velocity pressure in the duct:

$$SP_h = h_e + VP_d \quad (6)$$

$$SP_h = (F_s)(VP_s) + (F_h)(VP_d) + VP_d \quad (7)$$

where F_s and F_h are loss coefficients for slot and hood entries, and VP_s and VP_d are slot (or opening) and duct velocity pressures.

The design of hooding for hot processes such as pouring molten CuCl requires different considerations than for cold processes. As heated air rises, it mixes turbulently with the surrounding air, increasing the air column diameter and volumetric flow rate. The diameter of the column can be approximated by:

$$D_c = 0.5\, X_c^{0.88} \quad (8)$$

where D_c is column diameter at the hood face, $X_c = y + z$ is the distance from the hypothetical point source to the hood face, y is the distance from the process surface to the hood face, and z is the distance from the process surface to the hypothetical point source. The velocity of the rising hot air column can be calculated as

$$V_f = 8\frac{(A_s)^{0.33}(\Delta T)^{0.42}}{X_c^{0.25}} \quad (9)$$

where A_s is area of the hot source, and ΔT is the temperature difference between the hot source and the ambient air. The diameter of the hood face must be larger than the diameter of the rising hot air column to assure complete capture. The hood diameter can be determined as follows:

$$D_f = D_c + 0.8y \quad (10)$$

The total hood air flow rate is

$$Q_t = V_f A_c + V_r(A_f - A_c) \quad (11)$$

where A_c is area of the hot air column at the hood face, V_r is the required air velocity through the remaining hood area, and A_f is the total area of hood face.

5.3 Fans

To move air in a ventilation or exhaust system, energy is required to overcome the system losses. Although this energy can be provided by natural convection or buoyancy, most systems require a powered air moving device. Such devices can be divided into two basic classifications: ejectors and fans. Ejectors have low operating efficiencies and are used only for special material handling applications. Fans are the primary air moving devices used in industrial applications and are considered in this investigation. Fans can be divided into three groups: axial, centrifugal, and special types. Generally, axial fans are used for higher flow rates at lower resistances and centrifugal fans for lower flow rates at higher resistances.

Axial fans come in three types: propeller, tubeaxial, and vaneaxial. Propeller fans are used for moving air against low static pressures and are used commonly for general ventilation. Tubeaxial fans (duct fans) contain narrow or propeller type blades in a short, cylindrical housing normally without any type of straightening vanes. Vaneaxial fans have propeller configurations with a hub and airfoil blades mounted in cylindrical housings that normally incorporate straightening vanes on the discharge side of the impeller. Vaneaxial fans are more efficient than other axial fans and generally develop higher pressures, but are usually limited to clean air applications.

Centrifugal fans have three basic impeller designs:

- Forward curved, with impeller blades that curve toward the direction of rotation. These fans have low space requirements, low tip speeds, and quiet operation. They are usually used against low to moderate static pressures such as those encountered in heating and air conditioning work and supply air systems. This type of fan is not recommended for dusts or particulate that could adhere to the short curved blades, cause imbalance, or reduce performance.
- Radial impellers, with blades that extend straight from the hub. The housings are designed with their inlets and outlets sized to produce material conveying velocities. These impeller designs range from "high efficiency minimum material" to "heavy impact resistance". The radial blade shape resists material build up. This fan design is used for most exhaust system applications when particulates pass through the fan. These fans usually have medium tip speeds and are used for exhaust systems handling clean or dirty air.

- Backward curved, with impeller blades inclined opposite to the direction of fan rotation. This type usually has higher tip speeds and provides high fan efficiency and relatively low noise levels with “non-overloading” horsepower characteristics. In a non-overloading fan, the maximum horsepower occurs near the optimum operating point so any variation from that point due to a change in a system resistance results in a reduction in operating horsepower. This type of fan is chosen here for the molten CuCl pouring station.

Fan selection involves not only finding a fan to match the required flow and pressure considerations but also air stream characteristics, operating temperature, drive arrangement, and mounting. Fan size is determined by considering performance requirements, as well as inlet size and location, fan weight, and ease of maintenance. The most efficient fan size may not fit the physical space available. Fan noise is generated by turbulence within the fan housing and varies with fan type, flow rate, pressure, and efficiency. Noise ratings are usually obtained from the manufacturer. Most fans produce a “white” noise (a mix of frequencies), although radial blade fans also produce a pure tone at a frequency equal to the blade passage frequency [19]:

$$BPF = RPM \times N \times CF \qquad (12)$$

where *BPF* is in Hz, *RPM* is rotational speed in rpm, *N* is number of blades, and *CF* is a conversion factor (1/60). The backward inclined type of impeller design is generally the quietest.

Various accessories (e.g., dampers, variable pitch blades, speed control) can alter fan performance, and may be required on systems that vary throughout the day or for flow rate reduction in anticipation of future requirements. Fan size, operating RPM and power are usually obtained from a rating table based on required air flow and pressure. Tables are based on fan total pressure *FTP* or fan static pressure *FSP*:

$$FTP = (SP_{outlet} + VP_{outlet}) - (SP_{inlet} + VP_{inlet}) \qquad (13)$$

$$FSP = SP_{outlet} - SP_{inlet} - VP_{inlet} \qquad (14)$$

For a given pressure, the highest mechanical efficiency can be expressed as

$$\eta = \frac{Q \times FTP}{CF \times PWR} = \frac{Q \times (FSP + VP_{out})}{CF \times PWR} \qquad (15)$$

where the conversion factor is *CF* = 6362.

5.4 Ventilation for Heat Control

Ventilation for heat control in a hot industrial environment is a specific application of general industrial ventilation. A heat control ventilation system must follow a physiological evaluation in terms of potential heat stress for occupants in a hot industrial environment. For normal body function, the deep body core must be maintained within the acceptable range of about 37℃. The basic heat balance can be expressed as

$$\Delta S = (M - W) \pm C \pm R - E \qquad (16)$$

where ΔS denotes change in body heat content, *M* total metabolism, *W* external work performed, *C* convective heat exchange, *R* radiative heat exchange, and *E* evaporative heat loss. To obtain ΔS, measured data are required for metabolic heat production, air temperature, air water vapour pressure, wind velocity, and mean radiant temperature. The rate of convection *C* between skin and surrounding ambient air is [21]:

$$C = 95 V_a^{0.6} (t_a - t_{sk}) \qquad (17)$$

where V_a denotes air velocity, t_a air temperature and t_{sk} the mean weighted skin temperature, usually assumed to be 35℃. A practical approximation of the infrared radiant heat exchange *R* (in W) for a person wearing conventional clothing is:

$$R = 92(t_w - t_{sk}) \qquad (18)$$

where t_w is the mean radiant temperature in ℃ . The evaporative heat loss *E* for people can be expressed as [16]:

$$E = 1.46 V_a^{0.6} (\rho_{sk} - \rho_a) \qquad (19)$$

where ρ_a is water vapour pressure of ambient air and ρ_{sk} is water vapour pressure on the skin. It is impractical to attempt to control process heat in hot industries, but an air conditioned booth or cab can be utilized to keep the operators reasonably comfortable.

5.5 Make-up Air

The air removed from a workplace by the exhaust IV system must be replaced with clean air, either passively through passive infiltration or mechanically via a make-up air supply system. In industrial facilities, infiltration is usually inadequate to provide the needed replacement air. When there is insufficient make-up air, the workplace becomes air starved, placing an added burden on the exhaust system and reducing the quantity of air exhausted to an unacceptably low level. An uncontrolled influx of replacement air to the work area can cause air distribution and temperature regulation problems elsewhere in a plant. Compensating measures to maintain comfort in those areas ultimately lead to the use of more energy than required by a well-designed make-up air system. Hence, make-up air systems to replace exhausted air are desirable.

Make-up air is usually supplied by a roof-mounted supply fan equipped with air filters and heating and/or cooling equipment. Direct-fired heating of air with gas is the most energy-efficient method. The combustion products are usually not a concern because high air flow rates provide sufficient dilution. Indirect-fired heating is used in gas-fired air make-up units where the products of combustion are vented outdoors. The distribution of make-up air in the workplace is also important from the standpoint of worker comfort, as well as proper operation of the exhaust system. Cross drafts over the tops of vented tanks should be avoided as they reduce the effectiveness of a local exhaust ventilation system. Rather than provide 100% outside air for make-up air, exhaust air can sometimes be recirculated into the workplace, reducing HVAC energy requirements. But this technique is not used in the present design because of the risk of reintroducing contaminated air into occupied areas. The requirements for a safe, reliable recirculation system are [20]:

- A primary air-cleaning system designed to reduce all contaminants in the recirculated air below the TLV;
- A secondary air-cleaning system of equal or greater efficiency in series with the primary system or a reliable monitoring device to analyze a representative sample of the recirculated air;
- A warning-alarm system with provisions for immediate bypass of the recirculated air, if contaminant concentrations exceeding limits are detected by the monitor, or the air-cleaning system requires attention.

Local exhaust ventilation and make-up air systems require substantial space allocations, both overhead and on the roof. Careful consideration should be given to these requirements when designing the ventilation system. Interference between supply and exhaust ductwork can be avoided through proper planning and layout. Locating the make-up air unit as far from the scrubber/exhaust fan as practical helps reduce the possibility of large ducts (headers) crossing each other. This may reduce the overall building height requirement and costs. The distance between the make-up air intakes and exhaust gas discharges and their orientations relative to the prevailing wind direction should not permit contaminants into the building make-up air supply.

5.6 Air Cleaning Devices

Air cleaning devices for particulate contaminants are divided into two groups: air filters and dust collectors. Air filters are designed to remove low dust concentrations of the magnitude found in atmospheric air. They are typically used in HVAC systems where dust concentrations seldom exceed 1.0 grains per 30 m^3. Dust collectors are usually designed for the much heavier loads from industrial processes where the air or gas to be cleaned originates in local exhaust systems or process stack gas effluents. Contaminant concentrations vary from less than 0.1 to 100 grains or more for each cubic meter of air or gas. Therefore dust collectors must be capable of handling 100 to 20,000 times greater flows than air filters [21].

Dust collection equipment designs are numerous, utilizing many principles and featuring a wide variation in effectiveness, first cost, operating and maintenance cost, space, arrangement, and materials of construction. Currently, there is no accepted standard for testing and/or expressing the efficiency of a dust collector. Options include high efficiency, high cost, high voltage electrostatic precipitators requiring minimum energy, high efficiency and moderate cost equipment such as fabric or wet collectors, or lower cost primary units such as the dry centrifugal group. When the cleaned air is discharged outdoors, the required degree of collection depends on plant location, the nature of contaminants (salvage value and potential as a health hazard, public nuisance, or ability to damage property), and government regulations. In remote locations, damage to farms or contribution to air pollution problems of distant cities can influence the need for and importance of effective collection equipment.

A safe recommendation is to select the collector that allows the least amount of contaminant to escape and is reasonable in first and maintenance costs, while meeting all prevailing air pollution regulations. Contaminant characteristics also affect equipment selection. Chemicals emitted may attack collector elements or corrode wet type collectors. Sticky materials, such as metallic buffing dust impregnated with buffing compounds, can adhere to collector elements, plugging collector passages. Particle size, shape and density rule out certain designs. Contaminants in exhaust systems cover an extreme range in concentration and particle size. For the molten CuCl pouring station, dust collectors are reasonable for a local exhaust ventilation system. The air cleaning system does not need to capture all contaminants, as some contaminant escape is not very harmful if released after passing through the dust collector. Energy cost and availability affects the total energy requirement for each collector type that can achieve the desired performance. An electrostatic precipitator, for example, may be advantageous despite its high initial cost because its lower pressure drop saves energy.

5.7 Dust Disposal

Methods of removal or disposal of collected materials vary with the material, process, quantity, and collector design. Dry collectors can be unloaded continuously or in batches through dump gates, tickle valves, and rotator locks to conveyors or containers. Material characteristics can influence disposal problems. Packing and bridging of dry materials in dust hoppers, and floating or slurry forming characteristics in wet collectors, are examples of problems that can be encountered. The four major types of dust collectors for particulate contaminants are electrostatic precipitators, fabric collectors, wet collectors, and dry centrifugal collectors.

Dry centrifugal collectors are chosen for the molten CuCl pouring station, to separate entrained particulate from an air stream by the use or combination of centrifugal, inertial, and gravitational force. Collection efficiency is influenced by 1) particle size, weight, and shape, with performance improved as size and weight become larger and shape becomes more spherical; 2) collector size and design, noting the collection of fine dust with a mechanical device requires equipment designed to utilize mechanical forces for the application; 3) velocity, since pressure drop through a cyclone collector increases approximately as the square of the inlet velocity and there is an optimum velocity for a collector design, dust characteristics, gas temperature and density; and 4) dust concentration, noting mechanical collector performance increases as the concentration increases.

High efficiency centrifugals exert higher centrifugal forces on dust particles in a gas stream. Because the centrifugal force depends on peripheral velocity and angular acceleration, improved dust separation efficiency is obtained by increasing inlet velocity, making the cyclone body and cone longer, using a number of small diameter cyclones in parallel, and placing units in series. While high efficiency centrifugals are not as efficient on small particles as electrostatic, fabric, and wet collectors, their effective collection range is appreciably beyond that of other mechanical devices. Pressure losses of such collectors range from 75 to 200 mm of water.

5.8 Worker Position Effect

The position of a worker relative to the flow direction is an important parameter in determining the breathing zone concentration (ACGIH, 2004). Position 2 in Fig. 5 shows a worker oriented with his back to the air flow. Immediately downstream of the worker, a zone of reverse flow and turbulent mixing occurs due to boundary layer separation. Contaminants released into this region mix into the breathing zone resulting in exposure. Position 1 shows a worker oriented at 90º to the flow direction, in which case the reverse flow zone forms to the side and there is less opportunity for the entrainment of contaminants into the breathing zone [21]. A side orientation is recommended in the current design.

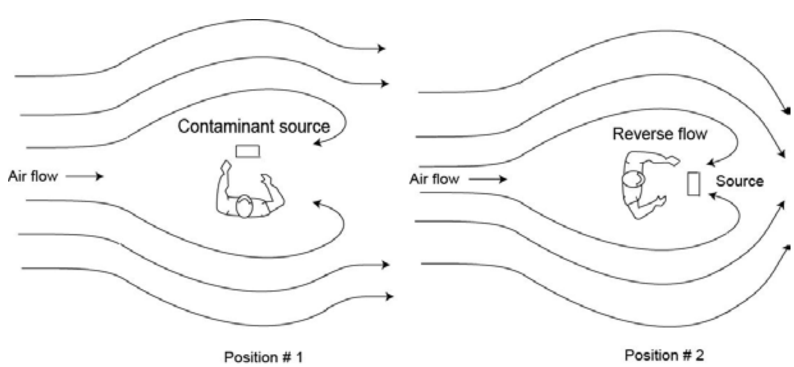

Fig. 5 Worker position effect

5.9 Economics

The costs for industrial exhaust systems include capital costs for hoods, ducts, air cleaners, and fans (including installation); power costs for operating fans and air cleaners (which are dependent on fan efficiency); heating and cooling costs for the air that replaces the air exhausted; and maintenance costs.

Air volume is the biggest cost factor in many exhaust systems. With other factors constant, reducing the resistance or pressure loss in the system, decreases the operating cost. The air cleaner can cause the largest resistance, and oversizing it may reduce pressure drop. High hood slot or duct velocities also cause high pressure losses. Friction and turbulent pressure losses vary with the square of velocity. Applying the principle of air flow resistance is difficult as many other cost factors are linked to duct diameter and air velocity. Thus reducing operating costs by lowering system resistance may increase other costs. Nonetheless, static pressure can be reduced by avoiding long runs of small-diameter ducts or other ducts with high pressure losses, and locating the fan so that branch ducts enter the main duct as close to the fan as possible, if ducts with high static pressure are unavoidable. Fan costs (capital and operating) increase with high air flow and resistance; duct costs rise as duct diameters are increased to lower system resistance [22]. Duct velocities of 9-13 m s^{-1} general provide a good balance between duct installation cost and fan operating costs.

Table 1 summarizes the economic impact of air flow and resistance. All costs except hood costs decrease or are unchanged by lowering the air volume. It costs more to provide hoods that are shaped and located to minimize the air flow needed for proper operation than it costs for less effective hoods. Likewise efforts to reduce system resistance decrease or do not change all costs except duct and perhaps air cleaner costs. To reduce system resistance, duct diameters are usually increased, wider duct elbows are installed, turning vanes are added to elbows, and angled rather than perpendicular branch duct entries into main ducts are specified. Also gradual rather than abrupt duct enlargements and contractions are needed. Air cleaner costs may increase because, if the air cleaner causes significant resistance, an oversized or different air cleaner type may be needed to reduce resistance. Either of these air cleaners likely costs more than the minimum air cleaner.

Table 1. System cost factors compared with air flow and resistance

	Effect of reducing air flow needed for proper operations	Effect of reducing system resistance
Capital costs		
Hoods	Increases	No change
Ducts	Decreases	Increases
Air cleaner	Decreases	May increase
Fans	Decreases	Decreases
Make-up air system	Decreases	No change
Operating costs		
Power for fan	Decreases	Decreases
Maintenance	No change	No change
Heating/cooling make-up air	Decreases	No change

Duct costs depend on the amount and kind of material used for duct construction and the labour to fabricate and install the ducts. Sheet steel is used in most duct systems although stainless steel, polyvinyl chloride, and other materials are popular in corrosive or special environments. The amount of steel used in ducts increases sharply with large-diameter ducts. There is little operating cost associated with ducts except the need for cleaning when plugging occurs. Fan capital costs vary with air volume and fan static pressure. For moderately sized systems, the potential capital cost savings from designing a system with slightly lower volume or fan static pressure is not significant. The costs are reduced from long-term lower electrical power consumption in operating the fan. Operating costs are calculated from the fan brake horsepower, with a higher horsepower requirement implying higher power costs to operate the fan. The capital costs for air cleaners depend on the type and size. Operating costs include electric power for blowers, pumps and electrostatic precipitators; replaceable media in filters and carbon adsorption beds; fuel for incinerators; and water and other chemicals for scrubbers. Labour and final disposal costs for the waste removed from the air cleaner must also be considered.

Electricity is the usual power for the exhaust fan, the make-up air fan, and the air cleaner. Fan power costs can be calculated from the brake horsepower rating of the fan motor. Power costs vary with the utility company supplying the power and the class of service. Although future projections of power costs are difficult, they likely will increase in the future. Cooling make-up air is more expensive than heating on a degree-for-degree basis. For every 0.5 m^3 s^{-1} exhausted through hoods, roughly 3-4 tons of refrigeration must be added to the air conditioning load. Operating costs are calculated from the air conditioning unit and the electrical power to run it.

6. RESULTS AND DISCUSSION

As pointed out earlier, the latent heat of phase-change can be recovered from the solidification of molten CuCl so as to improve the overall thermal efficiency of the Cu-Cl cycle.

CuCl vapour may be produced during the pouring of molten CuCl into the heat recovery chamber. Since the heat recovery fluid is transported outside of the system, the CuCl vapour may be entrained by it. The entrainment quantity can be estimated from the partial pressure of CuCl vapour. From thermodynamics, the saturation partial pressure is determined by the equilibrium vapour pressure of CuCl at the operating conditions. Figure 6 shows the equilibrium vapour pressure of the CuCl at different temperatures based on experimental data reported in past studies [23-27].

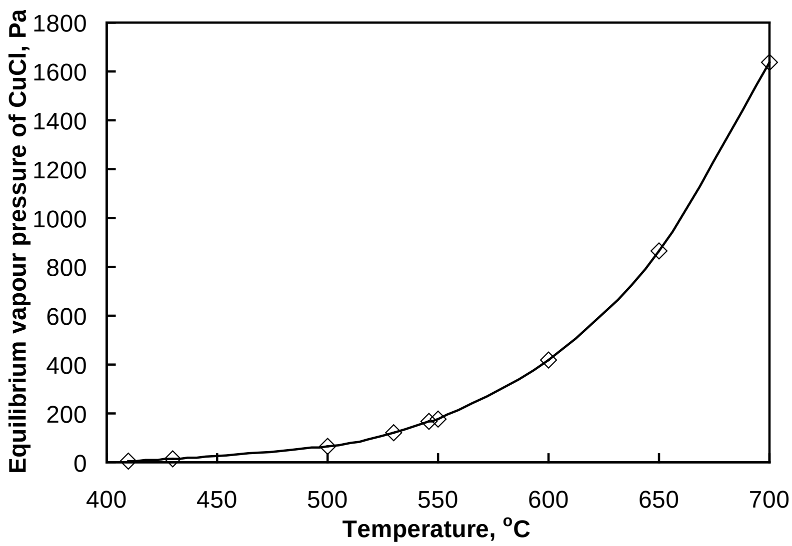

Fig. 6 Equilibrium vapour pressure of CuCl at different temperatures

Table 2 shows the maximum cuprous chloride vapour production rate in the heat recovery system, for 4-step and 5-step variations of Cu-Cl cycle, based on an industrial hydrogen production rate of 100 tons/day. It shows the temperature of the molten salt leaving the oxygen reactor. The production rate at a temperature of 600ºC is also estimated by considering a scenario of accidentally losing temperature control of the oxygen production reactor. In this case, the maximum temperature of the oxygen reactor is the heat source temperature because the oxygen production reaction is endothermic. The temperature increase will increase the CuCl vapour production rate, as the vapour pressure of CuCl increases with temperature. P_{tot} represents the total pressure of the heat recovery system. The production rate of CuCl vapour will decrease when increasing the total pressure of the system. However, a higher operating pressure may lead to an increase in the operating costs.

Table 2. Production rate of CuCl vapour in the Cu-Cl cycle

P_{tot} (bar)	Production rate of CuCl vapour (kg/day)			
	4-step		5-step	
	T=530ºC	T=600ºC	T=530ºC	T=600ºC
1.2	2,514	8,584	5,028	17,168
1.4	2,155	7,358	4,310	14,715
1.6	1,886	6,438	3,771	12,876
1.8	1,676	5,723	3,352	11,445
2	1,508	5,150	3,017	10,300

Reduction of the Cu-Cl hazards is dependent of the heat recovery method. Atomization is one of the options for recovering heat from the molten CuCl due to its advantages of a reasonably high heat recovery efficiency and the combination of solidification and granulation into a single process. In this method, the molten salt is introduced by a spray nozzle, or a spinning disk or rotary cup. Using a spinning disk or rotary cup, a centrifugal force carries the fluid to the edge of the disk or cup and spins the fluid off the edge. The liquid forms sheets that then break into droplets. The spray pattern tends to move radially away from the disk or cup in all directions. Drying gas, e.g., nitrogen or helium, passes through a perforated plate and flows upward to form a counter current flow with descending CuCl droplets/particles so as to provide good mixing and thereby to promote good heat recovery [5].

In the atomization methods, CuCl vapour is entrained by the atomizing gas; the entrainment amount can be estimated with equilibrium vapour pressure data (see Table 2). The heat recovery fluid should be circulated in a closed system; otherwise the CuCl vapour may enter the environment. To utilize the recovered heat, a secondary heat exchanger must be set up for heat transfer from the heated atomizing gas to an endothermic process in the Cu-Cl cycle. After the atomizing gas leaves the heat exchanger, it circulates back to the atomization chamber. In the loop, the build-up of deposited CuCl on the walls of the secondary heat exchanger and circulation pipes could be an issue due to the solidification of the entrained CuCl vapour in the drying air. The deposition of CuCl is caused by the temperature decrease when the heat of atomizing gas is extracted in the secondary heat exchanger, so changing the structure of the heat exchanger may not bring a significant reduction of the CuCl build-up.

Another method for recovering heat from molten CuCl is casting/extrusion technology in a coaxial cylinder. Molten CuCl enters the inside channel at about 530°C. A heat recovery fluid (air or water) flows in the shell side of the annulus, in a counter-current manner. The solid layer of the molten salt grows along the channel until all molten salt in the channel is solidified. A screw extruder is set into the solidified material at the exit of the channel. Once the molten material is cooled and solidified, it is removed by the extruder to prevent plugging of the channel. In the casting method, the heat recovery fluid is not in direct contact with the hazards so the generated steam does not carry the CuCl vapour and high purity steam can be generated. The whole pouring system should be confined.

Face velocity, the velocity measured in the plane of the opening of the enclosure, is an important design parameter. For toxicity substances, an average inward velocity of 0.76 m s^{-1} is recommended [19]. Figure 7 shows the required volumetric air flow rate, Q, as a function of the area of openings of the enclosure, A. Reducing the area of openings to a minimum reduces the volumetric air flow rate requirement.

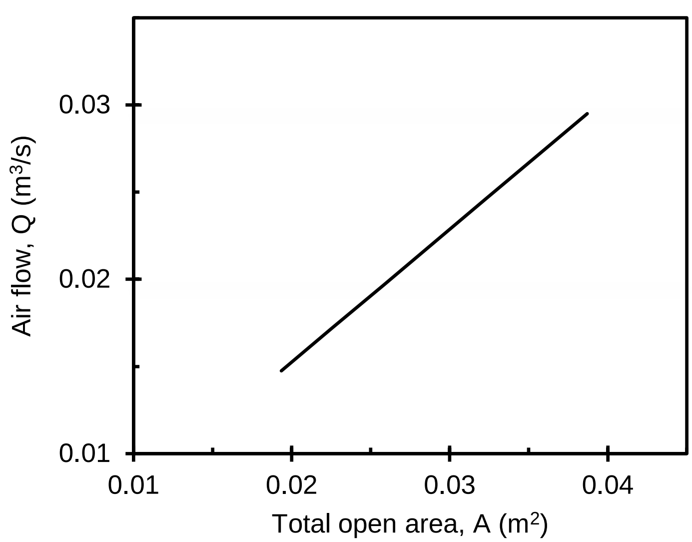

Fig. 7 Air flow rate as a function of the total area of openings

7. CONCLUSIONS

The preliminary design of a system to handle molten CuCl pouring in an industrial plant has considered the local exhaust system and hoods. If the original hood selection is inadequate, no matter how well the ducts and fan are designed, the system will probably never reduce airborne contaminants sufficiently. Hood selection is based on the characteristics of the contaminants and their dispersal, and the plant layout. Based on the worker position effect, the side orientation is investigated. The resistance to air flow through the hoods, ducts, air cleaners, and components is considered so that the fan size needed to move the correct amount of air against the system resistance can be determined. The costs involved in building and operating a ventilation system, and ways to minimize them, show that, for small systems that draw a few thousand cubic meters per minute or less against low static pressure, the potential for financial savings is limited. But the savings can be significant for larger systems or systems with high static pressure loss.

NOMENCLATURE

A	area, m^2
BPF	blade passage frequency, Hz
C	rate of convection, W
D	diameter, m
E	evaporative heat loss, W
P	pressure, bar
Q	air flow rate, $m^3\ s^{-1}$
R	radiative heat exchange, J
S	body heat content, J
SP	static pressure, Pa
T	Temperature, °C
V	velocity, $m\ s^{-1}$
W	external work, J

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