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HEAT AND HUMIDITY IN MINES

PSYCHROMETRY

Psychrometry is the study of the properties of moist air and is useful to engineers concerned with heating, cooling, and ventilating buildings. Psychrometry is the subject which deals with the properties of **gas-vapor mixtures**.

Virtually all mines produce water from the strata and/or dust. Mining engineers have a particular interest in psychrometry for two reasons.

First, if we are to comprehend fully the thermodynamic processes that occur in ventilation circuits then variations in humidity must be taken into account. For example, strata heat may be emitted into a wet airway without there being a corresponding increase in air temperature. The process of evaporation increases the energy content of the air-vapour mixture. This may be termed a **latent** (or hidden) rise in the heat content of the air as there is no commensurate increase in temperature and, hence, no indication on an ordinary thermometer.

Alternatively, if there were no liquid water present, then the strata heat would be directed immediately to the airstream, causing a temperature rise of the air that would be sensed by a thermometer. This is an increase in the **sensible heat** of the air.

These examples illustrate that if we are to predict quantitatively the climatic effects of strata heat, water inflows, machines or air coolers, then we need to have methods of analysis that take **humidity** into account.

The **second reason** for the study of psychrometry is the effect of heat and humidity on the human body.

PSYCHROMETRIC PROPERTIES OF AIR

Humidity

It is defined as the water-vapour content of the air.

Normal atmospheric air in most of the cases is humid. Humid air is also called moist air. The capacity of air to hold moisture increases with temperature. But, one should not be in confusion that in summer, air should be more humid compared to other seasons. This is because air may have more capacity to hold water, but we require source of water as well. Also, even if air has high water content at higher temperature, but it may not be saturated or have higher relative humid compared to air having low water vapor content but more relative humidity at lesser temperature. This is because relative humidity is not only governed by temperature of air/atmosphere (dry bulb temperature) but also wet bulb temperature.

Now, let us discuss the different ways of expressing humidity.

Relative Humidity

It is defined as the ratio of vapour pressure at a temperature to the saturation vapour pressure at that dry bulb temperature. It should be kept in mind that for calculating relative humidity, saturation vapour pressure is taken at dry bulb temperature and not at wet bulb temperature. Numerically it can be expressed as:

$$\text{Relative humidity} = (e/e_{sd}) \times 100\%$$

Specific Humidity

It is defined as the mass of water vapour present in kg per kg of dry air. Mathematically it is expressed as follow.

$$Sp\ Heat = 0.622 \frac{e}{P_b - e} kg / kg\ der\ air$$

Where,

e = Vapour pressure or Partial pressure due to water vapour (kPa)

P_b = barometric pressure (kPa)

Absolute Humidity

It is defined as the amount of water vapor present in a unit volume of air, usually expressed in kilograms per cubic meter. It is mathematically expressed as

$$m' = \frac{10^2 e}{461.9T}$$

Where,

m' = absolute humidity (kg/m^3)

T= temperature in Kelvin (K)

e = Vapour pressure or Partial pressure due to water vapour (kPa)

This is rarely used in analysis. Volume of air passing through ventilation system keeps changing because of variation in temperature and pressure. Thus, use of absolute humidity is *discouraged*.

Dew Point

It is defined as the temperature at which air attains saturation and a further addition of water vapour leads to dew formation because of condensation of water vapour. It is rarely used to indicate the moisture content of the air/atmosphere. The temperature recorded in this case is *dry bulb temperature*. At dew point, dry bulb and wet bulb temperature are same.

Example

The dry and wet bulb temperature recorded in a mine are as follows:

D.C. Pit bottom	*V.C. Pit bottom*
Dry – Wet	*DRY – WET*
33^0C – 30^0C	*35.2^0C – 34^0C*

The quantity of air circulating is 6000 m^3/min. The water content of saturated air at normal atmospheric pressure is given below. At 33^0C = 35 gm/m^3 and at 35.2^0C = 38.5 gm/m^3. Calculate the amount of water carried out by air from the mine per day.

Solution

Difference between dry and wet bulb temperature at D.C. pit bottom = 33 - 30 = 3^0C.

$\therefore$ Relative humidity of intake air = 100 - 3 x 7 = 79%

$\therefore$ Water content of intake air = 35 x 0.79 = 27.65 g/m^3

Difference between dry and wet bulb temperatures at U.C. pit bottom = 35.2 - 34 = 1.2^0C.

$\therefore$ Relative humidity of return air = 100 - 1.2 x 7 = 91.6%

$\therefore$ Water content of return air = 38.5 x 0.916 = 35.27 g/m^3

$\therefore$ Amount of water carried out by ventilating air = 35.27 - 27.65 = 7.62 g/m^3

The amount of water carried by ventilating air per day

= (7.62 x 6000 x 60 x 24)/(1000 x 1000) = 65.836 tonnes

Dry-Bulb Temperature

It is the temperature recorded by using a conventional thermometer. The thermometer without muslin cloth in the psychrometer records dry-bulb temperature. It just reads the ordinary temperature of the air and is a measure of sensible heat content of the air. Its unit is °F or °C or Kelvin (K).

Wet-Bulb Temperature

It is recorded by thermometer having wet muslin cloth on its bulb. The temperature recorded is in general lower than dry-bulb temperature because of cooling effect of the evaporating water of wet muslin cloth. They are equal only when air is in saturation and no net evaporation of water from wet muslin cloth takes place. Wet-bulb temperature can never be higher than dry-bulb temperature. From the definition point of view, it is defined as the temperature at which water vapour evaporating into the air can bring down the air in saturation adiabatically at that temperature. It is a measure of the evaporating capacity of the air. Its unit is °F or °C or kelvin (K).

Barometric pressure

It is simply the pressure recorded by a barometer at a particular place. It is usually expressed in kPa.

HEAT IN MINES

Human beings are capable of working efficiently within a certain range of temperatures. Temperature is concerned with degree of hotness. Temperature of a substance or body is liable to change when we have a source of heat. Heat always flow from high temperature to low temperature body. This flow can take place in any one of the three ways of transferring heat-conduction, convection and radiation.

These modes of transferring heat mainly cause flow of sensible heat.

Through evaporation, transfer of latent heat takes place. In this case, we do not sense the rise in temperature, but heat content of the body is increased. In underground mines, there are many sources of heat which cause rise of temperature of air during its travel in mine airways. The condition may worsen if the temperature of the air increases beyond a certain limit. The situation becomes more critical especially when humidity of air also increases simultaneously. In such situation, we require **air conditioning of mine air**. We have to set up refrigeration plants, spot coolers, etc. so as to ensure comfort, safety and high working efficiency of workers in mines. On the other hand, in areas with extreme cold climatic conditions, we need to supply heat to the air on the surface before sending it to underground mines.

MAJOR SOURCES OF HEAT IN MINE

The **major sources of heat** in underground mines are:

- Strata heat
- Auto-compression
- Machinery and lights
- Underground water

Strata Heat (Rock heat)

Strata heat is a major source of heat underground mines. In some cases especially in deep mines, it becomes intolerable and we require installation of refrigeration systems so as to provide safe and comfortable working conditions.

The term strata heat means the heat emitted from the surrounding rocks and getting added to the mine atmosphere. Subsurface rocks mainly have their heat reservoirs in the core portion of the earth, which emits heat and that heat gets transferred to the upper part of the earth like mantle and crust. In crust part of the earth, mining is practiced.

Thus, whenever we go for subsurface mining, strata heat is a major factor that has to be considered while planning ventilation system so as to create comfortable working conditions.

Geothermal Gradient

The term 'geo' means earth, 'thermal' means heat and 'gradient' means change in a particular quantity with respect to distance. Thus, we can define '**geothermal gradient'** as the change of heat/temperature of subsurface rocks with respect to distance, $\Delta t/\Delta z$. This increase is approximately 1 °C every 70–110 m in the case of deep metal mines.

The geothermal gradient in °C/100 m for a given formation can be calculated from conductive heat-transfer theory.

$$q = kA\frac{\Delta t}{\Delta Z}$$

Rearranging, $$\frac{\Delta t}{\Delta Z} = \frac{q / A}{k}$$

The overall gradient can then be determined by cumulating the gradients for the individual formations.

The heat that is present is usually the residual heat from planetary accretion from Earth's earlier eras and the decay of radioactive isotopes. Both of these things cause the terrestrial nucleus to be around 5700 °C and its heat flow outwards to be an average of 0.07 W m^{-2}. This heat penetrates the mine.

Geothermal step

In mining, we generally make use of the term '**geothermal step'**, which is defined as the depth per degree centigrade rise in temperature. If we look carefully, we can easily make out that, *geothermal step is inverse of geothermal gradient.*

Both geothermal step as well as geothermal gradient may vary from place to place depending upon the types of the rocks found in the area, thermal properties of the rock, presence of underground water reservoirs, etc. It is also greatly influenced by the age of the rock, and igneous activities going in the region.

Thermal Conductivity of Rocks

Thermal conductivity of a rock is defined as the heat flow across a surface per unit area per unit time when a particular temperature difference exists in a unit length perpendicular to the surface.

It depends on following factors:-

- Chemical composition of the rocks (rocks are aggregates of minerals)
- Water content of the rock
- Temperature
- Pressure
- Radioactive decay (if any) etc.

Thermal conductivity has units of W/(m°C)

Heat Flux

It is defined as the heat rate (J/s) per unit area, the direction of heat flux is in the direction of negative temperature gradient. The earth's heat flux ranges from 0.04 -0.06 W/m^2. We take average value as 0.05 W/m^2 for calculation purpose.

Factors Determining Strata Heat Flow in Mines

Heat flow into mine airways from the strata is very complex in nature. It involves a large number of variables/factors that significantly influences the rate of heat flow. These variables may be classified into two broad categories i.e., primary factors and secondary factors.

Primary factors

- Geothermic gradient
- Thermal properties of rock like thermal conductivity, thermal capacity
- Difference between virgin rock temperature (VRT) and dry bulb temperature
- Length of the mine airways
- Humidity and pressure

Secondary factors

- Roughness of rock surface
- Shape and size of airway
- Air Volume flow
- Nature of air-rock interface
- Inclination of airway
- Age of the airway

Auto-compression

Air entering through a shaft or incline gets compressed by the weight of the air column in the shaft or the incline. In this process, the air gets heated up. This happens because of conversion of its potential energy into enthalpy. Increase in enthalpy either increases pressure or internal energy or both, causing temperature of air to rise.

Change in potential energy is given by

$$H_2 - H_1 = (Z_1 - Z_2)g + q_{12}$$

where H = enthalpy (J/kg)

Z = Height above datum (m)

q_{12} = Heat added in the airway (J)

The term $(Z_1 - Z_2)g$ is always positive for the downcast shaft and is unavoidable. While q_{12} depend on whether the surrounding rock surface is at higher temperature or lower temperature compared to the air travelling in the airways. It also depends on whether the surface is dry or wet.

If no heat is transferred with the surrounding while air travels down the shaft, it is called *adiabatic auto-compression*. In other words, it is also called *adiabatic lapse rate*.

Let us calculate change in temperature of air travelling down the shaft. For a general airway surface, it is given as

$$\Delta T_d = \frac{(Z_1 - Z_2)g - L\Delta X}{C_{pm}} \ ^0C$$

Where,

ΔT_d = change in dry bulb temperature of the air (°C)

L = latent heat of vaporization (J/kg)

Z_1 , Z_2 = height above datum line (m)

g = acceleration due to gravity (m/s^2)

ΔX = increase in water vapour content of air due to evaporation (kg/kg dry air)

$$C_{pm} = \frac{1+X}{c_{pd} + c_{pv}X} = \frac{1+X}{1005 + 1884X}$$ = specific heat of moist air (J/kg °C)

If the airway is completely dry, the term $L\Delta X = 0$. In wet shafts, there will be considerable cooling due to evaporation. The values obtained are likely to be affected by other sources of heat. The general estimation can be made by the following relation:

$$\frac{\Delta T_d}{\Delta Z} = 0.966^0 C/100m$$

$$\frac{\Delta T_w}{\Delta Z} = 0.438^0 C/100m$$

Another way of estimating change in temperature is using equation of adiabatic compression given by

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{(\gamma-1)/\gamma}$$

where,

T_1 and T_2 = dry bulb temperature

p_1 and p_2 = atmospheric pressure

γ = ratio of specific heats of air (1.42)

The **reverse process of auto-compression** i.e. **auto-decompression** is observed in the upcast shaft when air escapes out the mine while moving upwards in the upcast shaft. In this process expansion of air takes place causing decrease in its temperature. Due to this, droplets of water with dust gets accumulated on fans in the upcast shaft thereby reducing its life and increasing its maintenance cost.

Machinery & Lights

Most of the machines used in mines are known to add sensible heat to the mine air either through friction, electric losses etc. We all know that it is hard to design a machine with 100 % efficiency. Thus, all machines add heat to the mine air by non-mechanical work produced by them. Different types of machinery used in mines can be classified on the basis of their source of power supplied. They are

- **Electrical equipments** The main electrical equipment utilized in the mines is fans, haulage, road headers, conveyors, hoists, pumps, transformers, LHDs, shearer loaders, etc. Most of the inputs provided to them are converted into heat except for the part which is utilized in doing the work against gravity.
- **Diesel engines** Diesel equipments are less efficient. Compared to electrical units, they have approximately 1/3rd efficiency. As a thumb rule, the heat generated by a diesel engine is taken to be 2.8 to 3 kW per kW of the rated power of the equipment. Heat load from a diesel engine is also calculated on the basis of average rate of fuel consumption by it in a shift. The heat produced by a diesel engine appears in three ways each of which may be roughly of the same magnitude: (i) heat from the radiator and machine body (mostly sensible heating) (ii) heat in the exhaust gases (as latent heat of water vapour and

sensible heat of other by-product gases) (iii) the remaining as useful shaft power. It is further converted to heat by frictional processes as the machine performs its tasks (as sensible heat). Thus, diesel equipments do not only add heat load but also add moisture to the mine air.

- **Compressed air run equipments/machinery** In general, compressed air machinery does not add any heat to the mine air. It is because the heat added due to the frictional work done by compressed air machinery gets compensated by the heat absorbed by the exhaust of the compressed air unit. However, addition of heat to mine air takes place when hot compressed air is taken down the shaft in pipelines.

Underground Water

In underground mines, water is a major source of heat. It transfers heat to mine air through the process of evaporation. Hence, we can say that it mainly adds latent heat to mine air. Thus, it increases wet-bulb temperature of mine air. Evaporation of water causes rise in humidity. Thus, water has a significant role in heat addition as well as moisture addition to mine air.

Sources of water in underground mines are:

- Ground water – water from rock reservoirs such as hot water fissures
- Mine-water – water used for services such as drinking, drilling purpose, fire fighting, drainage etc.

Ground water has its source in rock reservoirs and therefore its temperature will be either equal or greater than the surrounding rocks.

Heat added to mine air by evaporation of water can be reduced by adopting following techniques:

- transportation of water in closed and insulated pipes
- constructing covered ditches
- allowing water flow in return airways
- grouting the rocks

To compute heat load addition to mine air because of water in underground mines, the following equation can be used:

$$q = G_w C_w (T_1 - T_2)\, J/\sec$$

where

q = heat load due to water (J/sec)

G_w = rate of water flow (kg/sec)

C_w = specific heat of water (J/kg °C)

T_1 = temperature of water at the point of emission/source in the mine (°C)

T_2 = temperature of water at the point of exit/sink in the mine (°C)

MINOR SOURCES OF HEAT IN MINES

The **minor sources of heat** in mines include

- Human metabolism
- Oxidation
- Blasting
- Rock movement
- Pipelines
- Energy losses in airflow

Human Metabolism

Due to metabolism, human beings produce heat even when they are at rest. The heat produced is dependent on various factors such as

- manual work being done
- body surface area of the man
- level of mental stress, etc.

Heat produced is proportional to all these factors. Men at work produce more heat and the amount of heat produced goes on increasing as the work becomes more vigorous. A man transfers heat to the surroundings in three different ways:

- through heat loss from body surface
- through respiration
- through frictional work

Following gives the average heat produced by human body under different situations.

Nature of work	Light work (e.g. winch driving)	Moderate work (e.g. fitting)	Hard work (e.g. shovelling)
Metabolic heat rate (W/m^2)	90	180	270

In general, the body surface area of a miner/worker can be taken as 1.8-1.9 m^2. We can see from table that the heat added by miner/worker is not a significant one. It can be significant only when the local working of the mine (e.g., face) is not properly ventilated.

Metabolic heat balance in human body

The food taken by human beings serves as fuel for their body. The oxidation of food is an exothermic reaction. The energy released in the process is called metabolic energy. This metabolic energy produced by oxidation of food is used for working against gravity, growth of body (accumulates in the body) and rest is transferred to the surroundings. The energy released depends upon the oxygen consumed in the oxidation of food. More is the amount of oxygen consumed, more is the energy produced. When we work hard, the breathing rate increases. This increases consumption of oxygen. That's why as the amount of work load increases, the amount of metabolic heat produced by human beings increases.

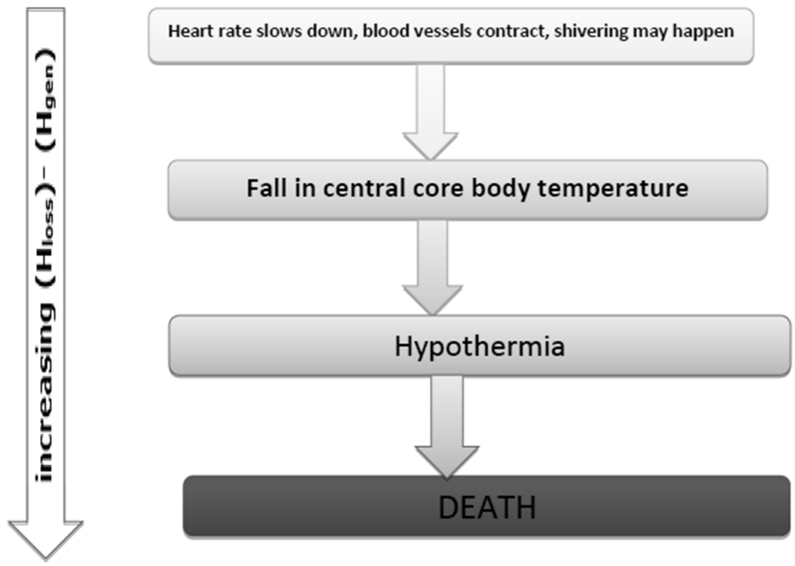
The metabolic heat produced can be transferred to the surrounding by convection, radiation, respiratory exchange (breathing) and evaporation.

- **Mean Skin Temperature and Core Body Temperature**. Human body can be thought of divided into two-parts (interior to exterior) namely - central core body and the skin. Blood vessels separate these two. Human body has to be maintained at 36.9°C for proper physiological functions. The heat to maintain this temperature is provided by oxidation of food. This temperature is called temperature of the central core body (T_c). However, T_c may vary ±1°C depending up on the atmospheric conditions and individual response to the atmospheric conditions. Hence, we can say that the normal central core body temperature of human being lies in the range of 35.9 − 37.9°C. Blood acts as cooling agent for skin. In general, mean skin temperature (T_{sk}) is lower than T_c. At 34°C, the skin does not feel any sensation of hotness or cold with the environment. T_{sk} depends on many factors including dry bulb and wet bulb temperature, rate of perspiration, types of clothing, etc.
- **Hypothermia**. A state when the rate of heat production in the body is lower than the heat removed to the surrounding leading to reduction of the central core body temperature i.e., below 36°C.
- **Hyperthermia**. A state when the rate of metabolic heat production is more than the rate of metabolic heat removal, leading to increase in the central core body temperature i.e., above 37.9°C.

EFFECTS OF HEAT AND HUMIDITY

Heat Loss Greater than Heat Generated

When the rate of heat loss to the surroundings (H_{loss}) is more than the rate of metabolic heat generation (H_{gen}), the effects observed can be shown as in following figure.



Heat Loss Lower than Heat Generated

This is more common in the mine atmosphere.

This condition to a miner/worker may arise due to the combined effect of wet-bulb and dry-bulb temperatures, psychrometric properties of the mine air and velocity of air-current. Besides these factors, the effects observed on an individual are also dependent on 'time duration of exposure' to such condition. This condition generally arises when the dry bulb temperature of the air increases beyond a certain limit such that heat removal from the body is reduced. If the dry-bulb temperature of air/atmosphere goes on increasing, heat removal from body through radiation and convection may reverse the directions (heat may be added to the human body from the atmosphere through the process of radiation and convection). In such cases, the metabolic heat from the body is removed through evaporation of sweat. Sweat, produced by the sweat glands, adds moisture to the surrounding air. If the humidity of the air is already high, the evaporation of sweat is reduced and therefore the central core body temperature of an individual rises rapidly. Even if air is moderately humid, sweat glands reduce their capacity to produce sweat with time. A time comes when no more sweat is produced due to fatigue of the sweat glands. If exposure to such environmental conditions continues, it may lead to **heat stroke** ultimately leading to the death of the person.

Following table lists the physiological effects on a miner/individual with the rise in temperature of air and human body.

Effect of increase in the dry bulb temperature

Dry bulb temp (^{0}C)	Body temp. (^{0}C)	Physiological effects
≤ 25	---	Normal blood circulation, no observable effect, heat removal from body mainly through convection and radiation
25 - 29	---	Heat removal rate increases, slight rise in central core body temperature, vaso-motor control of body increases blood circulation
29 - 37.5	---	Body starts sweating, heat removal mainly through evaporation
≥ 36.9	36.9	Body temperature equals dry bulb temperature, heat transfer through convection and radiation reverses the direction, heat removal from body through evaporation only.
---	39	Heart beat rises above 140 beats /min, fatal
---	41	Unconsciousness, coma, may lead to death
---	43.3	Sudden death
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Effect of High Wet Bulb Temperature

The difference between the wet bulb temperature and dry bulb temperature decide the relative humidity of the air. The lesser is the difference, the more is the relative humidity. We know that air at high relative humidity hampers rate of evaporation.

At higher wet bulb temperature, the reduction in evaporation of sweat causes body temperature to rise and in extreme case if the rise in temperature exceeds 2°C, heart beat becomes faster, which on continuation may lead to unconsciousness or even death.

Following table lists the rise in body temperature with wet-bulb temperature.

Increase in body temperature with wet bulb temperature

Wet bulb temp (K)	Rise in body temp (K)
≤ 302.15	0.11- 0.66
302.65 – 304.85	0.33 – 0.77
305.35 – 307.65	0.66 – 1.55
≥307.65	1.44 -1.90

COOLING POWER OF AIR

It can be demonstrated empirically that, in a hot environment, the capacity of a person to do work is limited by and somewhat less numerically than the cooling power of the air in which that person is working, when both are expressed in comparable units. Cooling power is a measure of the ability of the air to remove metabolic heat. It is usually measured by an instrument such as the **kata thermometer**.

Cooling power of air is the effect of

- the temperature of air at the working place,
- the relative humidity of air and
- air velocity.

The cooling power measured in W/m^2 (amount of heat removes from the human body per second per unit surface area) It depends mainly on the wet bulb temperature and the air velocity.

Methods of improving cooling power air

- By increasing the quantity of ventilating air.
- By circulating drier air
- By cooling or refrigeration of the circulating air
- By regenerative cooling
- Using devaporized compressed air
- Cooling of mine air at the face by using ice or liquid air

By increasing quantity of air

- This should be the first option to be tried for improving hot and humid conditions in mines.
- The increased quantity of air not only dilutes the heat produced in the mine but also produces a higher air velocity which improves the cooling power of mine air.
- In deep mines some extra quantity of air is necessary for suitably dealing with the heat produced in the mine from variety of sources.
- In addition, an estimate of heat addition in a mine from different sources should be made and the air quantity requirement for dilution of this heat evaluated for improving the cooling power of mine air.

If q is the amount of heat added in any part of the mine per unit time (kW), then for heat balance

$$MH_a = q + MH_i$$

Or, $$Q = q/(H_a - H_i)\rho$$

Where

M = mass flow-rate of dry air, kg/s = $Q\rho$

Q = quantity of air flowing, m^3/s

ρ = apparent density, (kg of dry air per m^3 of moist air)

H_a = allowable enthalpy of air, kJ/kg of dry air

H_i = enthalpy of in-flowing air, kJ/kg of dry air.

By drying of mine air

- In deep and hot mines where air temperature is high, maintaining the air dry helps in improving the working conditions.
- There is no economical process of drying the air as such except refrigeration.
- Drying of mine air by passing it over desiccants like calcium chloride, magnesium chloride or silica gel is costly.
- Also the advantages gained by drying is greatly compensated by the heat produced by absorption which raises the air temperature.
- It is better to take adequate care to see that the air does not pick up moisture in the mine and hence is maintained dry.
- This is done by adopting dry mining by preventing the evaporation of water oozing out from the strata.

By refrigeration of circulating air

- Refrigeration of mine air is necessary when its temp, becomes excessive so that no father increase in the quantity of air would improve environmental conditions.
- Air is cooled and dehumidified by the refrigeration plants so that it is saturated at 275 to 278 K.
- It is then conducted to the working faces as such or mixing with a stream of uncooled air so as to obtained the desired face temps.
- Hence a refrigeration plant should be designed to have a capacity sufficient for cooling the farthest face.

Calculation of cooling load of a refrigerator

If total heat added to the mine air from different sources = q, kW

The required cooling load (qc) is given by the heat balance equation

$$q_c = q + Q\rho\,(H_i - H_a),\ \text{kW Where}$$

Where Q = quantity of air flowing, m3/s

ρ = apparent air density, (kg of dry air per m^3 of moist air)

H_a = allowable enthalpy of air, kJ/kg of dry air

H_i = enthalpy of in-flowing air, kJ/kg of dry air.

By regenerative cooling

- This concept is only theoretical and yet to be adopted in practice.
- If a gas of high density and low specific heat like CO_2 circulated in a close circuit down the upcast shaft and up again through the downcast shaft, the heat developed due to auto-compression of CO_2 will be dissipated into the upcast air while the cooling due to auto expansion will cool the downcast air.
- This not only produce cooling of the downcast air but also increase the natural ventilation.

By circulating devaporized compressed air

- Devaporization is done by over compressing the air by 500-650 kPa.
- It is then passed through a heat exchange system where the over compressed air is cooled by a current of cool devaporised compressed air.
- The cooled over compressed air is now employed to run an air motor. In doing so it expands to the normal working pressure and also cools to 273 K.
- At this temperature all the moisture in compressed air is liquefied and removed from it.
- The dry and cool compressed air is now circulated through heat exchanger to cool the over compressed air.
- The devaporized air is now sent down the mine where it is used to run air motors, drills etc. at the face.
- The exhaust air from these machines gets substantially cooled by expansion.
- This coupled with dryness of the air helps in keeping down the temperature and humidity at the face.

KATA THERMOMETER

The first Kata thermometer was developed in the 1920s by Sir Leonard Hill (UK) to determine the cooling power of an environment while measuring thermal comfort. This was an alcohol filled thermometer with a large cylindrical bulb, with markings at 35°C and 38°C on the graduated stem.

In order to determine the total cooling power of air, the bulb is covered with a wet cotton cloth and the apparatus is heated in hot water (50 to 60° C) in a thermos flask. It is then wiped dry and suspended for the combined exposure to the prevailing temperature, air velocity and radiation, but not humidity. The time in seconds for the fall of the temperature from 38 to 35°C is noted. By dividing the calibration or the Kata factor, determined beforehand for the thermometer, by the total number of seconds it took to cool from 38 to 35°C, the Kata cooling power of air in W/m^2 is obtained.

The wet-kata cooling power is related to the wet bulb temperature and the air velocity by the following relations:

$$K = (14.65 + 35.59v^{1/2})(309.65 - T) \quad \text{for air velocity} < 1 \text{ m/s}$$

and

$$K = (4.19 + 46.05v^{1/2})(309.65 - T) \quad \text{for air velocity} > 1 \text{ m/s}$$

where K is kata cooling power in W/m^2

v = velocity of air in m/s

and T = wet bulb temperature in K.

Limitations of Kata Thermometer

A moderately working man produces about 165 W/m^2 of waste heat which has to be dissipated. In other words, a kata value of 165 W/m^2 should be sufficient for cooling a moderate worker, but it has been found that the rate of cooling of the kata thermometer is much faster compared to the human body, i.e. the cooling air is not 100% efficient for the human body. Hence, many authors put the kata cooling efficiency of air at only 20% which means that for comfortable working, the minimum wet-kata reading should be 165 x 5 = 825 W/m^2.

Also, the kata cooling power is not always consistent. The kata factor changes with temperature. A variation or 10% occurs if the air temperature changes from 283 to 303 K. Moreover, with low air velocities and large differences between dry- and wet-bulb temperatures, the wet-kata cooling power has a considerably low value.

So, we see that that the kata thermometer offers no better measure of the cooling power of mine air than wet-bulb temperature, hence its use has long been discontinued m many parts of the world.

CONTROLLING MINE TEMPERATURE (AIR CONDITIONING)

Temperature-humidity control (air conditioning), one of the three functions of total mine air conditioning, is essentially heat control. It consists of those processes that are designed to regulate the sensible- and/or latent-heat content of the air: heating, cooling, humidification, and dehumidification. The heat content of the mine air is maintained within limits prescribed for the comfort, safety, and working efficiency of miners.

Mine air conditioning for temperature-humidity control becomes necessary when ventilation alone is inadequate to maintain acceptable atmospheric heat standards.

The climate in underground mines become more and more adverse with increase in the depth of mine, increase in the extent of mechanization etc. There is an increase in the temperature as mines become deeper. This results into adverse mining environment which is not suitable for comfortable working of miners.

In underground mines, it is not the high relative humidity which is more dangerous. Actually it is the **high wet bulb temperature**, which is more dangerous in mines. A relative humidity of 100 % at lower temperature gives a sensation of cooling, while at higher temperature like 25 degree Celsius or above, it gives a sensation of hotness.

We require **controlling** the mine climate, so that the working conditions can be made comfortable. As most of the heat produced in a working district is removed by air current, either we increase quantity of air or cooling of mine air when it's not possible to increase the quantity of air beyond a certain limit. Thus air can carry away more heat and helps in maintaining good working climatic conditions.

Relatively shallow mines in cold climates sometimes find it necessary to **heat air** being taken underground, for comfort reasons as well as for prevention of freezing in intake openings. As with cooling, heating installations range from small local units to large central systems.

Vapour Compression Cycle

The mechanical process of absorption of heat from one location and its transfer to and rejection at another place is termed **refrigeration**.

In the most commonly used form of refrigeration, the working medium or refrigerant alternates between the liquid and vapor phases. Hence such processes are called change of **state or vapor refrigeration**.

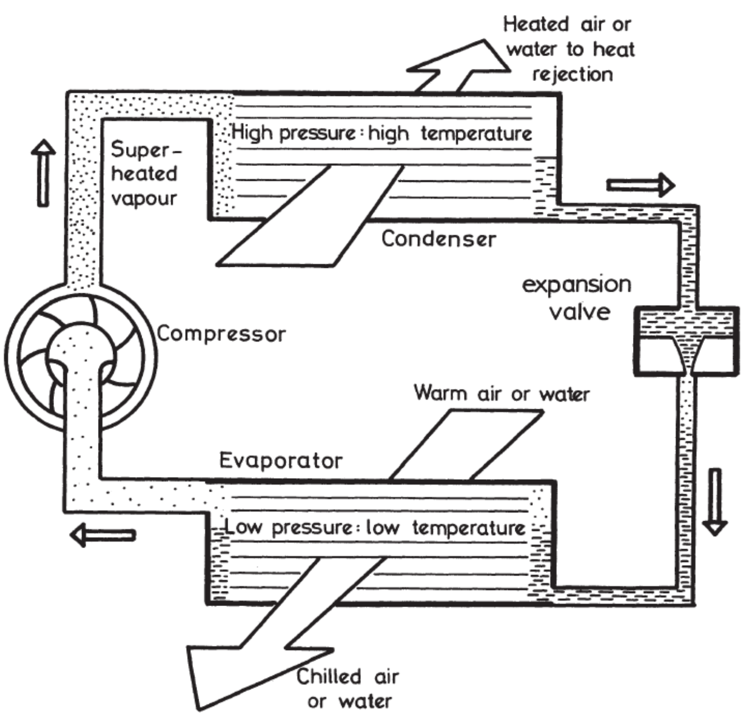
Of the several devices that have been developed to achieve a continuous refrigeration or heat pump effect, the most common is based on the vapour compression cycle. This may be used on small units such as air conditioning equipment fitted to automobiles or for very large scale cooling of mine workings where many megawatts of heat require to be transferred.

Cycle of four basic processes

- A refrigeration system consists of a cycle of four basic processes circulating a **refrigerant**, the heat-transfer medium. The purpose of the refrigerant is to absorb heat from a "source" **evaporator**) and discharge it through a "sink" (**condenser**).
- Some type of **vapor pump** must be located between the source and sink so that the energy absorbed by the refrigerant in the evaporator may be transferred to the condenser for discharge; it takes the form of a **compressor**.
- The final component of a vapor refrigeration system is an **expansion valve**, used to control flow rate and permit cooling of the refrigerant in its return to the evaporator.

Thus vapor refrigeration is essentially a **compression system**, involving **heat exchange** through a change of state of the refrigerant from **liquid to gas and then back to liquid**.

A vapor refrigeration cycle in schematic is represented by the block diagram given below.



The path of flow of the refrigerant and the changes it undergoes can be traced through the system as follows:

1. **Evaporator**: Refrigerant "boils" (evaporates), changing state from predominantly liquid to gas and absorbing heat from substance to be cooled, with no change in temperature.
2. **Compressor**: In the vapor state, refrigerant flows to compressor, where work is done in compressing it.
3. **Condenser**: Vapor condenses to liquid again, giving up heat without a temperature change.
4. **Expansion valve**: Temperature and pressure of liquid drops during expansion, as refrigerant completes cycle.

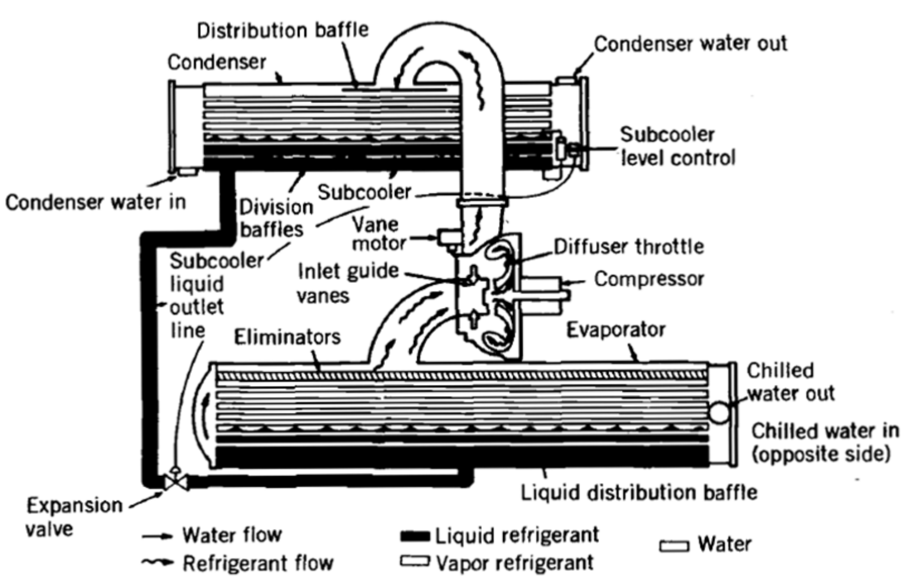
Refrigeration (Air Conditioning) Plant

The cooling of mine air is usually done by using **refrigeration plants**. This air conditioning helps in improving the working conditions. The Statuary limit in India for climatic conditions is 33.5°C Wet Bulb Temperature with minimum air velocity of 1m/s.

When simple methods of controlling the mine climate don't make an effect on mine environment then we have to go for artificial cooling of the air. This is done by refrigeration of mine air. We install refrigeration plants for this purpose. They are usually designed to produce tolerable environment condition throughout the year.

The commonly used refrigeration plant in mine is of **vapour compression type** i.e. compression system of refrigeration. In this type a liquid refrigerant is used to extract the latent heat of vaporization from mine air.

A typical refrigeration machine using a vapor cycle appears is shown below.



The plant shown employs a centrifugal compressor, the most common type, although reciprocating and rotary units are also used. Centrifugal compressors are more versatile and capable of handling large volumes of gas.

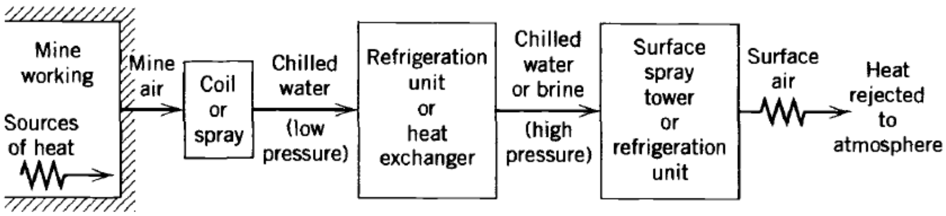
In mines, they are driven electrically, operate at efficiencies of 70-80%, and are capable of duties of 100-3000 tons refrigeration per unit.

The evaporator and condenser are nearly identical in appearance and have a shell-and-tube construction. In both cases, the refrigerant flows over the outside of the tubes. In the evaporator, chilled water or brine (acting as a secondary refrigerant or intermediate heat-transfer medium) flows in the tubes, while in the condenser, water or another coolant used to reject heat to the atmosphere in cooling towers or spray ponds occupies the tubes. Expansion is accomplished by automatic throttling valves of various designs; one valve is required for each stage of compression.

A variety of fluids, both liquids and gases, with good heat-transfer properties are used as refrigerants. Although **ammonia** is low in cost, it can be employed only in surface plants where leaks are not hazardous. For underground installations, the freon refrigerants [**chlorofluorocarbons (CFCs)**] have been most commonly used but are being phased out because they pose an environmental threat to the earth's ozone layer.

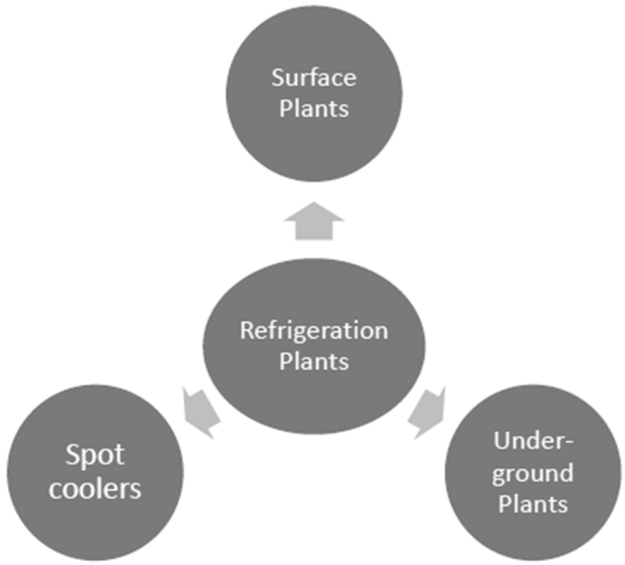
Design of a mine refrigeration plant commences with specification of the cooling load and selection of plant type, size (tons of refrigeration and chilled water requirements), and location (surface or underground). After choosing a suitable refrigerant, the cycle temperatures are established.

Schematic of heat-transfer circuits utilized in a conventional **mine air conditioning system** is given below.



Types of refrigeration plants

Based on the location of mine refrigeration plants, their classification can be as shown in following figure.



Classification of refrigeration plants based on location

Surface Plant

In this type of plants, air is cooled on the surface and then taken to underground via intake shaft. This cool air extracts the heat from the environment.

Advantages

- Simplicity
- Lower cost as cheaper refrigerants are used
- Convenience of operation and inspection
- The disposal of waste heat can be easily done here
- Aid in producing large natural ventilation pressure because of the difference in the temperature of air in downcast shaft and upcast shaft.

Disadvantages

- Poor positional efficiency (positional efficiency can be defined as the ratio of effective cooling units produced at the working face to the total cooling units produced by the refrigerator).
- In deep shafts, because of auto compression cool air from the surface plant picks up much heat and thus become less efficient.

Underground Plant

- It is the next step in air cooling in which the cooling plant is entirely located underground.

- The air can either be cooled at the centrally located underground plant itself or at chilled water spray chamber near the face.
- Another method of cooling air is to use roadway cooler. Here the cooling coils should be positioned such that they are at minimum distance from the working place. The cooling coils get chilled water from refrigeration plant and cool the air.

Advantages

- It has high positional efficiency.
- The heating of cooled air due to auto compression is avoided here.
- It eliminates the need of surface-connecting pipe ranges and the pumping costs associated with this.
- It also avoids any environmental problems that may arise from surface plant.

Disadvantages

- The cost of refrigerant is more as non-toxic refrigerant has to be used here which costs four times as that of ammonia (commonly used in surface plants).
- The dissipation of the heat extracted from mine air is also difficult.
- Because of the dust deposition on the tubes of cooling pipes, it requires frequent cleaning. The dust deposition results into poor efficiency of heat transfer. This happens in dry and dusty mines.
- The capacity of these plants is usually small (up to 1.75MW). So a single plant may not be capable of serving the whole mine.

Spot Coolers

- These are small capacity refrigerating units, applied mainly to ventilate isolated hot workings. They are semi-portable in nature and have refrigeration capacities in the range 50 to 500 kW.
- Based on size or mechanism of refrigeration, they can be divided into two broad categories (i) Small spot coolers These have arrangement for direct cooling of air stream on the evaporator coils using evaporation of refrigerants. (ii) Big spot coolers These use some intermediate coolant such as water to cool the air.

Advantages of spot coolers

- Maximum positional efficiency of all the three
- Helps in dust suppression at the face
- Compactness
- Very effective in deep metal as well as coal mines

Disadvantages of spot coolers

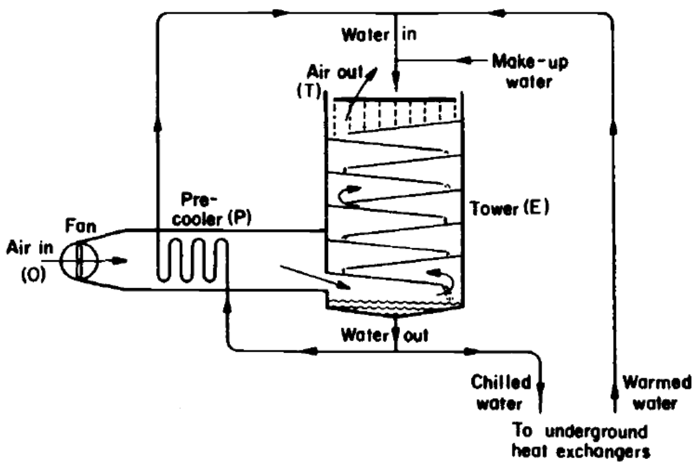
- Though it cools face, leaves the rest of mine air hot
- Very expensive

COOLING TOWER

A cooling tower is a heat-exchange device that cools liquids, usually water, by a combination of heat and mass transfer. The principal means of heat transfer involved in cooling towers is evaporative cooling. Evaporation of a small portion of the water being sprayed or percolated in the air of the tower removes sensible heat from the remaining water.

The theoretical limit to which water can be cooled by spraying it into air is the wet-bulb temperature of the air.

A schematic of a surface cooling tower equipped with a precooler and intended to produce chilled water is shown in the figure.



From point O to point P, the air is precooled before entering the tower. It then is evaporatively cooled from P to E as it rises in the tower, evaporating some of the spray water and cooling the remainder. This process generally reaches saturation. With continued, prolonged contact between air and water, some sensible-heat transfer occurs by convection between E and T; the water is further cooled, and the air heated and humidified. The air is discharged, saturated, at T.

The line O to T symbolizes the overall process line; while the heat exchange cools the water, it produces a net heat gain in the air.

MEASUREMETER OF HUMIDITY

Concept of Wet-Bulb Temperature

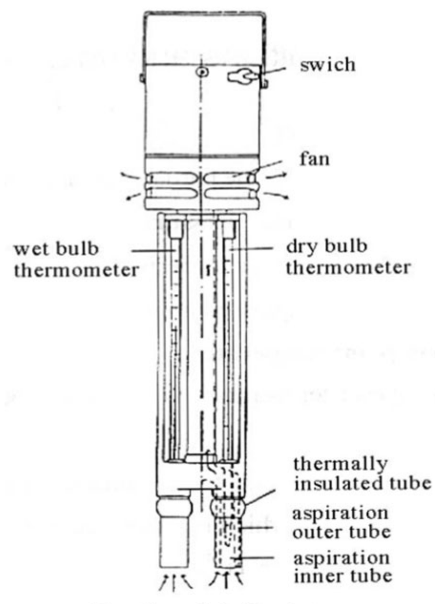
The water molecules in the wet muslin cloth take up energy from the neighbouring molecules and evaporate into the air. The evaporating molecules leave the thermometer surface with reduced energy. This causes depression in the temperature near the thermometer bulb. Thus, lower temperature is recorded. Thus, a difference between the temperature at the bulb and the atmosphere exists. This causes flow of heat from the air through convection. Initially this flow of heat from air to bulb with wet muslin cloth is slower than the rate of heat loss from the bulb with wet muslin due to evaporation. But, a stage comes when the rate of heat loss and rate of heat gained in the two opposite processes equal. At this point, no further depression in temperature of wet-bulb is observed. At equilibrium, the temperature of thermometer with wet muslin cloth on its bulb is taken as wet-bulb temperature.

Hygrometer

Hygrometer is used to determine the **relative humidity** of air.

Aspirated hygrometer (psychrometer)

The instrument consists of essentially two identical thermometers placed in sleeves, mounted side by side on a suitable frame, having a dry bulb to indicate the normal temperature of surrounding air, and a wet bulb kept continuously moist by a covering of fine cloth immersed in a reservoir, by which constant evaporation of moisture takes place thereby cooling it and depressing the wet bulb reading by an amount dependent on the degree of saturation of the air. The amount of saturation depends on the air pressure.



At the top of the two thermometers, a small spring-operated aspirator with clockwork mechanism is provided to suck in the air over them at a velocity of more than 2 m/s. When using the instrument, it must be held opposite to the flow direction to avoid temperature disturbances to the instrument caused due the body heat of the observer.

The instrument is carried in a leather carrying-case. The operating scale ranges from -10 to +60° C. The instrument is run for five minutes and simultaneously, and the reading of both the thermometers is noted for the psychometric difference between the dry and wet bulb temperatures.

Working

When the fan is kept on, the air through inner sleeves (metal sleeves provided at the bulb of each thermometer) and annular spaces enters the apparatus. The air travels through the central tube and goes out of the apparatus through the slits provided at the top near the fan. The fan is kept on for an interval of approximately 3 minutes. The fan should provide a velocity of more than 2m/s. This is done to ensure that wet-bulb thermometer attains a constant temperature.

Advantages

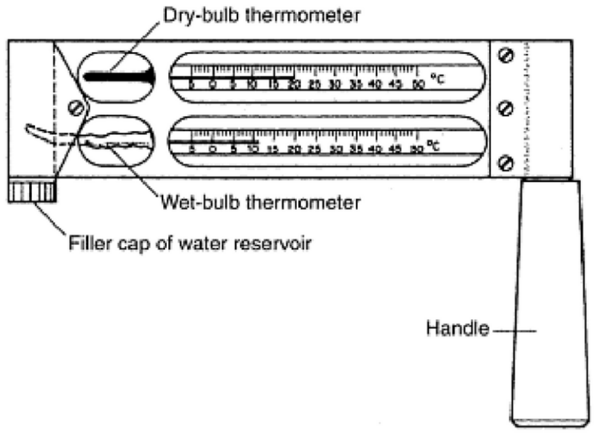
- It can measure humidity with an accuracy of ± 1%.
- The metal sleeves around the bulbs of the thermometers, shield the bulb from any radiation. This ensures that using this, we can accurately measure humidity in sunlit areas also.
- Easy to operate.

Precautions

- The instrument requires calibration with respect to the fan speed and hence the ventilation speed.
- The instrument should be hold away from observer’s body.
- The instrument should be held opposite to the direction of the flow when experiment/survey is being carried out in a strong air-current.

Whirling hygrometer (sling psychrometer)

The whirling hygrometer for measuring humidity consists of two thermometers that are turned by vigorously swinging the handle and exposing the thermometers to rapid air movement. The bulb of one thermometer is covered with a silk or muslin sleeve that is kept moist and this will record wet bulb temperature. The atmospheric humidity is determined by special tables from the difference in reading between the two thermometers.



The hygrometer contains two mercury-in-glass thermometers, one whose sensor is covered in wet muslin (close meshed cotton) or silk (wet bulb) and one normal (dry bulb). The hygrometer is whirled, hence passing moving air over the two sensors. This allows an effective measure of air temperature (dry bulb) and a measure of aspirated (air moved across sensor) wet bulb temperature.

The decrease in wet bulb temperature due to heat loss by evaporation, for a given air temperature, is related to the humidity of the environment. The atmospheric humidity is determined by special tables from the difference in reading between the two thermometers.

ASSIGNMENT

Q.1. (BPUT 2018, CSVTU 2020, JNTUH 2022, 2023, RGPV 2016, 7 marks): Define geothermal gradient. How do we calculate it?

Answer: Described in this module.

Q.2. (CSVTU 2020, VTU 2021, 4 marks): Define the following terms:

(i) Dry bulb temperature

(ii) Wet bulb temperature

(iii) Dew point

(iv) Relative humidity

Answer: Described in this module.

Q.3. (GTU 2021, 2023, 2 marks): Define Humidity.

Answer: Described in this module.

Q.4. (GTU 2022, 3 marks): Explain physiological effect of humidity.

Answer: Described in this module.

Q.5. (GTU 2020, 2021, 2 marks): Define Relative Humidity.

Answer: Described in this module.

Q.6. (BPUT 2018, 2019, 6 marks): What measures you would take to reduce the humidity in hot and humid underground coal mines?

Hint: Fans, spot coolers, refrigeration system

Q.7. (BPUT 2019, CSVTU 2020, JNTUH 2021, 2023, VTU 2021, 6 marks): Briefly discuss the important sources of heat in underground coal mines.

Answer: Described in this module.

Q.8. (GTU 2020, JNTUH 2021, 2022, RGPV 2016, 2020, 2021, 9 marks): Write effects of heat and humidity on human body/miners.

Answer: Described in this module.

Q.9. (GTU 2022, 2023, 4 marks): Explain an instrument used for measuring relative humidity in mines.

Answer: Hygrometer. Described in this module.

Q.10. (GTU 2021, 4 marks): Explain one method for determining the Relative Humidity.

Answer: Described in this module.

Q.11. (GTU 2021, 4 marks): Explain Hygrometer with sketch.

Answer: Described in this module.

Q.12. (GTU 2020, 2021, RGPV 2016, 4 marks): Describe working of Whirling Hygrometer in determining humidity..

Answer: Described in this module.

Q.13. (JNTUH 2022, 2023, 8 marks): What is the purpose, mode of action and inference from readings of a hygrometer used in mines?

Answer: Described in this module.

Q.14. (BPUT 2018, 2 marks): Differentiate between hygrometer and thermometer.

Answer:

- Hygrometer measures the moisture content in the air.
- Thermometer measures the degree of hotness or coldness of an object or environment.
- Both instruments are crucial for various applications, especially in mining, meteorology and climate control.

Q.15. (GTU 2020, 2021, 2023, 4 marks): Explain Kata Thermometer.

Answer: Described in this module.

Q.16. (BPUT 2018, 2019, 6 marks): Define "psychrometry". State the psychrometric properties of mine air.

Answer: Described in this module.

Q.17. (GTU 2023, 2 marks): Define Temperature.

Answer: Temperature is the measure of hotness or coldness expressed in terms of any of several scales, including Fahrenheit and Celsius. Temperature indicates the direction in which heat energy will spontaneously flow—i.e., from a hotter body (one at a higher temperature) to a colder body (one at a lower temperature).

Q.18. (CSVTU 2020, 8 marks): How do you measure relative humidity in coal mines? Explain comment on cooling power of mine air.

Q.19. (GTU 2020, 2022, 3 marks): Explain the method of determining cooling power of air.

Answer: Kata Thermometer. Described in this module.

Q.20. (VTU 2021, 8 marks): Explain the method to measure cooling power of air and velocity of air with neat diagram

Q.21. (JNTUH 2022, 2023, 8 marks): Explain the methods of improving of cooling power of mine air in underground mines.

Answer: Described in this module.

Q.22. (CSVTU 2020, 8 marks): Discuss the suitability and applicability of air conditioning in underground mines. Explain comfort conditions.

Answer: Described in this module.

Q.23. (JNTUH 2021, 15 marks): Explain the basic vapour cycle of air conditioning.

Answer: Described in this module.

Q.24. (BPUT 2019, 2 marks): What is cooling tower?

Q.25. (VTU 2021, 4 marks): Assuming density of water to be 1000 kg/m^3, calculate amount of heat added to the mine air by the following:

(a) 200 kW main underground pump pumping water at 5 m^3/min through a head of 150 m,

(b) A diesel LHD operating on level ground and consuming 7.5 kg of fuel per hour; heat content of the fuel is 40.1 MJ kg^{-1},

(c) A 4-kW battery locomotive operating on a level roadway, assume load factor of 0.3.