Safety of Industrial Plants

Lection 12

Ergonomics

Thermal environment

Contents and Goals

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Thermal environment

- The thermal environment is the working environment of the personnel, with particular reference to the thermal conditions of the organism and therefore to the thermal flows and to the thermal magnitudes affecting the body (feeling hot or cold).

- Man is treated as an energy system separated from the environment, subject to incoming and outgoing energy flows capable of transforming energy as a result of exergonic chemical reactions (i.e. releasing energy) linked to the metabolism.

Thermal environment

- The equation of energy balance of the body is as follows :

$$M + W + C + I + K + Cres + Eres + E = S$$

  - **M**, energy expenditure of metabolic origin (due to the vital functions of the human organism)
  - **W**, mechanical work produced outside
  - **C**, heat exchanged by convection
  - **I**, heat exchanged through radiation
  - **K**, heat exchanged by conduction
  - **Cres**, sensible heat transferred by means of breathing
  - **Eres**, latent heat transferred because of breathing
  - **E**, the lost energy for the evaporation of perspiration present on the body surface (perspiration / sweating)
  - **S**, energy accumulation

- The human organism is equipped with an internal mechanism of thermoregulation, which tends to change the individual quantities expressed by the equation in such a way as to oppose the occurrence of a non-null value of S.

- If S is positive or negative, a positive or negative accumulation of heat with a consequent increase or decrease in temperature of the core body will be registered.

Thermal environment

- The equation of energy balance is a function of seven parameters:
  - There are four parameters of environmental nature
  - There are three parameters of personal nature
- The parameters of environmental nature are as follows:
  - the air temperature Ta, mesured in proximity of the surface of the subject, at different heights so as to define an average value
  - the average radiant temperature Tr, which brings the exchange evaluation to the evaluation of only one size, such as to summarize the overall effect of the environment on the subject, and function of the difference of the temperature and of form factors, namely the geometry of interaction man - environment:
    - the black globe, is an instrument consisting of a bulb whose temperature is easily correlated to the average radiant temperature Tr, when steady state conditions are achieved
    - The irradiation I can be expressed by:

$$I = h\,(Tr - Ts)$$

    - Where (Tr-Ts) is the difference between the average radiant temperature and the skin temperature, and h is an appropriate exchange coefficient.

Thermal environment

- the third environmental parameter to consider is air humidity **r**
  - this parameter affects the evaporation of the water present in the pulmonary alveoli, or in the form of sweat on the skin

- In the end, it is necessary to consider the relative velocity v of the air, which affects the energy exchanges between man and the environment

Thermal environment

- The three factors of personal nature are :
  - The metabolic expenditure M, which is related to physical activity

1 MET = 58,2 W/m^2

	Metabolic Expenditure	
Activity	**W/m^2**	**MET**
Rest	46	0,8
Sitting	58	1
Standing	70	1,2
Office work	70	1,2
Light standing work	93	1,6
Moderate activity	116	2
Heavy activity	165	2,8

Thermal environment

- The three factors of personal nature are:
  - the clothing thermal insulation Iv, mainly function of the layer of air stably trapped between the fibers and between the worn clothing and the superficial layer of the body

1 CLO = 0,155 m^2°C/W

Clothing	Thermal insulation m^2°C/W	CLO
shorts	0,015	0,1
shorts, short-sleeved shirt, light socks and sandals	0,045	0,3
Light summer clothing	0,08	0.5
Light workwear	0,11	0,7
winter clothing	0,16	1
warm clothing	0,23	1,5

Thermal environment

- The three factors of personal nature are:
  - The third and last parameter to consider is the mechanical efficiency of the activity, η:

$$\eta = W / M$$

  - this value is not easily evaluated in the field
  - It is usually assessed by reference to the tables; however, in general, it appears to be lower than 0,1:
    - to produce one unit of work on the external environment, the body needs 10 energy units
- More physiological parameters to be taken into account, are:
  - The average skin temperature, **tsk**
  - the fraction of body surface which is wet by sweat

Moderate thermal environments

- There are three basic physiological conditions for well-being in a moderate thermal environment:
  - S = 0, i.e. the accumulation term of energy balance should be zero
  - modest changes in average temperature of the skin, however, included in the detected value by means of the following equation and expressed in ° C

$$tsk = 35,7 - 0,028 * M * (1 - \eta)$$

  - Thermal exchange by sweating comprised in a restricted area around the value expressed by

$$Es = 0,42 * [M * (1 - \eta) - 58]$$

Moderate thermal environments

- The evaluation of the thermal sensation in a moderate environment can be made on the basis of the following scale :
  - Very warm
  - warm
  - slightly warm
  - Neutral
  - Cool
  - Cold
  - Very cold

- To identify a link between the thermal sensation and the environment in which you are staying, a thermal load should be defined **(CT):**

difference between the thermal power that a generic model - in conditions of homeothermy - gives to the environment to remain in such conditions and the thermal power that would give the same environment if it were under conditions of thermal comfort

  - Warm sensation if $CT > 0$
  - Cold sensation if $CT < 0$
  - Neutral sensation if $CT=0$.

Moderate thermal environments

- Using an equation derived by Fanger based on an experimental experience, we can switch from the so-called CT to the so-called predicted mean vote (PMV), that is, the average score that a large population of individuals would express towards the thermal situation

$$PMV = \mathbf{CT \cdot (0{,}303 \cdot e^{(-0{,}036 \cdot M)} + 0.028)}$$

- The PMV is often not enough to give an accurate prediction of the level of satisfaction of the population in a certain environment.

- It is necessary to introduce another index, the so-called Predicted **Percentage of Dissatisfied** (**PPD**), which expresses the percentage of a predictable dissatisfied for a given value of PMV.

Moderate thermal environments

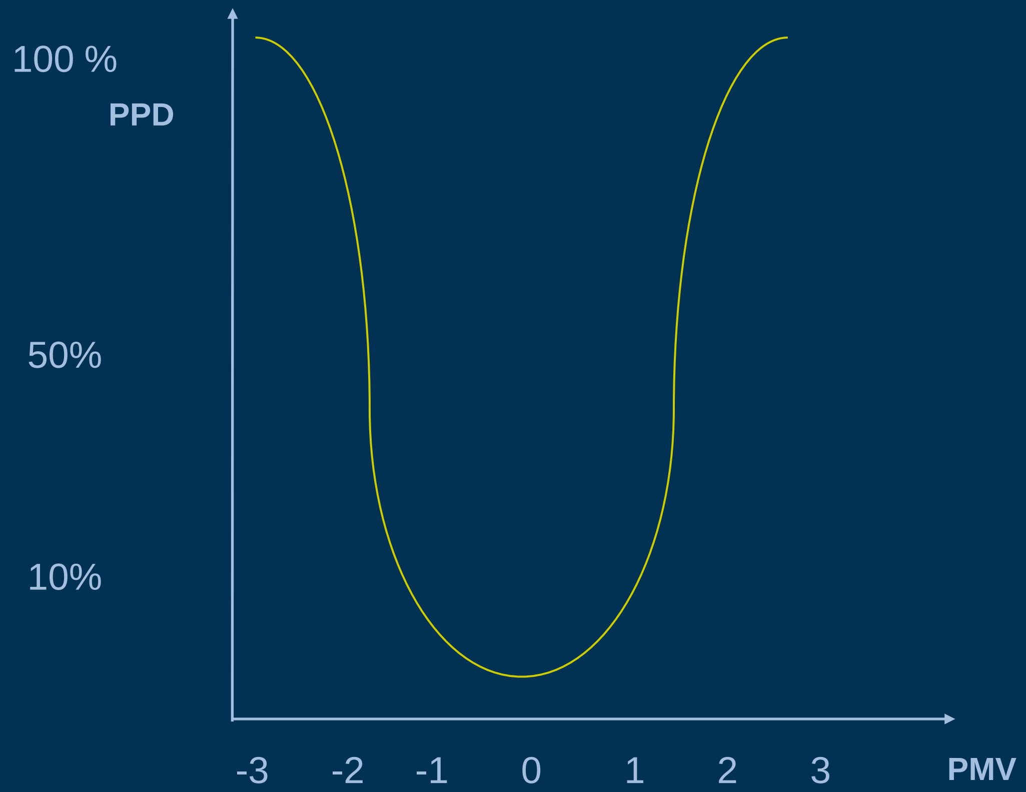


Chart of PPD as a function of PMV

Moderate thermal environments

- The values of the PMV and the PPD can be regarded as design parameters, requiring that any plant, either conditioning or heating plant, achieves at the center of the environment a PMV equal to zero.

- The magnitudes just viewed are used in technical diagrams that allow to quickly locate the comfort conditions:
  - once fixed the metabolic expenditure and thermal insulation of clothing, these diagrams show the optimal operating temperature
  - the operating temperature is considered by hypothesis the arithmetic mean between the air temperature and the average radiant temperature
  - in the case of the environments where the sources of radiation are less important the operating temperature coincides - practically - with the temperature of air.

Moderate thermal environments

- In the case of moderate environments, the humidity is not very relevant to the assessment of the comfort conditions.
- Fluctuations in the value have little effects on comfort :
  - It is not advisable, on the other hand, go down to below 30% relative humidity, the values in correspondence of which may in fact arise disorders
    - problems of dry mouth
    - burning to the eyes
    - risks of electrostatic discharges in environments with carpets.
  - In order not to make the environment unhealthy, is also not advisable to exceed the value of relative humidity higher than 70%, which could favor the occurrence of other drawbacks, such as the formation of molds, etc.

Moderate thermal environments

- There is almost always a deviation between the theoretical and the actual PPD, in consideration of two different groups of factors :
  - psychological and organizational factors; may be due to relocation, restructuring, changes in the corporate organization, installation of video terminals in unsuitable environments, etc.
  - factors of thermal nature; which, for example, strongly influence the feeling but are not considered in the criterion mentioned, which has the overall thermal budget as the main reference.
    - there are phenomena such as air currents, which, marginally affect the overall balance of the body, but strongly influence the thermal sensation
    - for this reason, in addition to the PMV and PPD, in moderate environments, more discomfort causes have to be considered.

Warm environments

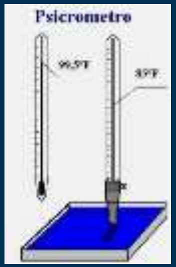
- An environment is considered warm when it tends to raise the temperature of the core body urging the thermoregulation system with a consequent increase of the blood circulation in the skin and subsequent emission of the sweat which evaporates.

- The set of these elements determine:
  - Increasing of heart rate
  - Increasing load of the cardiovascular system
  - excess of water and, therefore, of salts
    - if the flow of sweat required by the body to face the excessive heat was excessive, the body may not be able to achieve it and the temperature of the core body may increase, leading to cells deterioration
  - disorders affecting the digestive system
  - The so-called heat stroke is a classic example of uncontrolled rise in temperature of the core body

Warm environments

- The main standard indications tend to prevent the temperature of the core body increases beyond a degree centigrade compared to the optimal value.

- Warm environments are usually industrial environments where typical conditions occur:
  - High temperatures
  - High humidity
  - very intense sources of radiation
  - Frequently, air currents



- The criterion adopted for this type of environment is based on WBGT index, **Wet Bulb Globe Temperature (standard ISO 7243)**
  - The WBGT is an average temperature between the two temperatures, wet bulb with natural ventilation (tbu) (measured with the psychrometer) and the black globe (tg)

Warm environments

- Industrial environments are normally ventilated and the WBGT values to be considered are higher.

- The operator is often in motion and engaged in different activities:
  - it is difficult in this type of environments consider constant the metabolic expenditure or the WBGT value
  - The average values of WBGT are taken into account

Cold environments

- Cold environments can be of various types but, first of all, it is necessary to distinguish between the cold workplaces in the Nordic countries and the cold environments, more moderate, of which we are talking about.

- We consider cold environments those in which the temperatures can be in the order of some tens of degrees below zero, i.e. -25 °C, -30°C, -40°C.

- In these environments, a slow and moderate hypothermia my occur, which is normally associated with a loss of manual dexterity.

- Cold workplaces which satisfy the following conditions are taken into account:
  - Operative temperature   top = - 30 ± + 10 °C
  - Air speed   va = 0 ± 0, 5 m/s

Cold environments

- In cold environments, the main mechanism of thermoregulation is clothing.
- The criteria of reference are based on the equation of heat balance in thermal equilibrium :
  - the values of the isolation level related to clothing that cancel the first member of the equation in the specific environment are determined:

$$E(Iv) + M + W + C(Iv) + I(Iv) + Cres + Eres = 0$$

  - clothing intervenes both in the exchange by convection and evaporation of sweat, and in the exchange by radiation
  - the equation can be solved by taking as the unknown factor the clothing thermal insulation: the value we get is the one requested
  - The equation can also be solved with two boundary conditions:
    - considering an individual in terms of thermal neutrality:
      - the determined insulation value is required to determine thermal neutrality and homeothermy . In this case, the insulation is optimal.
      - The above condition is achieved by inserting into the equation of heat balance the skin temperature expressed by: $t_{sk} = 35{,}7 – 0{,}027 * M$
      - relatively to the heat exchange for sweating, it is assumed a fraction of wetted area equal to 25% of the body:
    - considering an individual with moderate cold feeling , we get a so-defined “minimum insulation”
      - the skin temperature is assumed equal to: t_{sk} = 30 ° C, in conditions of absence of sweating with W = 0.06

Cold environments

- In the end, we get two values of adoptable Iv, one maximum and one minimum:
  - If possible, the optimal one, or at least, the minimum value should be adopted
  - If not, the exposure has to be limited

- The exposure limit time is evaluated considering a reduction of body temperature, compatible with the needs of the body:
  - a reduction of the heat content Q of the body up to 40 Wh / m2 which corresponds to a change in body temperature of about **0,6 ÷ 0,7 °C** is tolerated
  - the duration of the exposure limit is evaluated, then, considering the relationship between the identified limit value Q and the accumulation term S derived by the equation of heat balance of the organism :

$$D = Q / S$$

    with $Q = -40\ Wh/m^2$

  - after having exceeded the limit time of exposure, the operator has to be removed from the environment in which it operates to be placed in a well air-conditioned environment in order to recover

Thermally difficult environments

- The thermal situation of a warm or cold environments, therefore, can be modified by varying
  - the metabolic expenditure
  - The clothing
- With reference to the first factor we can intervene by reducing the average values of the metabolic expenditure, for example:
  - By introducing breaks
  - by performing appropriate rotations of operators
  - By automating some operations
  - By shifting particularly heavy activities in most favorable moments from a climate point of view
- These actions, however, are of limited applicability, as it can be easily understood.

Thermally difficult environments

- With regard to clothing, it is necessary to evaluate the habits, desires and preferences by the operators.
  - air currents, for example, cause a lot of trouble; therefore, it is advisable to cover the parts of the body more susceptible, such as the ankles and the neck
  - Clothing must be as permeable as possible to water vapor, in order to prevent the accumulation of sweat inside
  - trying to promote cooling of the body of the individual by decreasing the level of thermal insulation of clothing
  - some inconveniences in an environment with hot air can be generated, for example, decreasing the level of clothing , the transfer of heat from the environmental air to the body by convection is favoured
  - in a warm, but dry enough, environment the reduction of clothing promotes sweat evaporation and thus represents a favorable intervention. The reduction of the level of clothing in industrial environments clashes, however, with the need for protection of operators and, therefore, is not always a feasible intervention
  - in a warm environment, water permeability is more required than insulation in order to ensure the permeability to perspiration
  - in the presence of strong sources of radiation, it is appropriate to wear reflective clothing equipped with a metal part capable of reflecting radiation.
  - in cold environments means of protection can be adopted in order to preserve parts of the body subject to cooling, such as hands, fingers, feet, ears, and nose, all characterized by a high ratio of dispersant surface and volume.

Thermally difficult environments

- We can also perform interventions of a more general nature:
  - Interventions on sources
    - On machines or parts of the plants, heat or cold sources:
      - Insulation
      - the reduction in the emissivity of the surfaces
      - talvolta, shielding or localized uptake of air
  - Identification of areas where they operators can have a break
    - in cold environments locally heat the operator
    - in warm environments increase the speed of air by fans with the adoption of adequate cooling air
  - General air conditioning
    - The indoor climate is also determined by the endogenous energies, produced by machinery and people who work in the environment
    - The above has to be taken in consideration, even for a right sizing of the plant
    - Very often, the need to have reduced energy consumption leads to achieve air-conditioning systems insufficient, with the need for subsequent and expensive modifications to the plant