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MEASUREMENT OF WBGT INDEX IN AXIAL FLOW AS THE MAIN THERMODYNAMIC PARAMETERS VARY

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Abstract: Heat stress is a common problem throughout industry that depends also on some climatic parameters, such as the mean radiant temperature, air humidity, velocity and temperature. WBGT (wet bulb globe temperature) index is assumed in international standards as thermal stress index in job environments. It can be estimated directly, following the ISO 7243, by means of globe temperature, natural wet-bulb temperature and air temperature measurements or indirectly by means air temperature, humidity and velocity, and the radiative medium temperature. The aim of the present work is the experimental comparison between the two different methodologies to evaluate the WBGT index. The analysis is carried out in a wide range of thermodynamic properties and also for air velocity less than 0.5 ms^{-1}.
Keywords: WBGT, natural wet bulb thermometer, globe thermometer, axial flow

1 INTRODUCTION

The metabolic activities of the body result almost completely in heat that must be continuously dissipated and regulated to prevent abnormal body temperatures. Heat stress in industrial working conditions is a serious concern and legislation has been developed with the intent of providing safer and healthier industrial environments. An environmental index combines two or more parameters into a single variable. Indices simplify the description of the thermal environmental and the stress imposed by an environment. The Wet Bulb Globe Temperature (WBGT) has been adopted as an index for the evaluation of severe thermal environments by virtue of its recommendation by the American Conference of Governmental Industrial Hygienists (ACGIH). In the model reported in ISO 7243 [1], the WBGT can be evaluated as follows:

$$\mathrm{WBGT} = 0.7 \cdot t_{nw} + 0.3 \cdot t_g \qquad (1)$$

where t_{nw} is the natural wet bulb temperature (°C), t_g is the globe temperature (°C) and when there are no significant sources of radiant heat. In particular, for environments characterised by high thermal stress (type S), the ISO 7726 [2] recommends the use of i) a natural ventilated thermometer to measure the temperature t_{nw} in the range between 5°C and 40°C, with an uncertainty of 0.5°C, ii) a globe thermometer to measure the globe temperature t_g in the range between 20°C and 120°C, with an uncertainty of 0.5°C (between 20°C and 50°C) and of 1°C (between 50°C and 120°C) and iii) a dry bulb thermometer to measure the air temperature t_a in the range between -40°C and 120°C, with an uncertainty of 0.5°C (between 0°C and 50°C).

The direct method, generally, does not allow accurate measurements and a direct traceability to the national or international standards. In fact, the globe temperature and the natural wet bulb temperature are not thermodynamic properties and can be only empirically estimated with the above-mentioned instrumentation.

The WBGT index can be more conveniently evaluated as a function of three thermodynamic parameters (the dry bulb temperature, the mean radiant temperature, the humidity ratio of moist air) and the air velocity. To this purpose several models, based on the mass and energy balance equations, were proposed in literature [3-5]. These models were not metrologically validated to allow a correct use in the calibration. In any case, the Sullivan model [3] is, actually, one of the most widespread. Furthermore, a difference of approximately 1°C between the direct and Sullivan's indirect methodology has been recently found in the case of air temperature equal to the mean radiant temperature [6].

In the present paper the authors carry out experimental tests to compare the direct and Sullivan indirect methodologies in accordance with the ISO 7243, in axial flow as the thermal and fluid dynamic parameters vary.

2 MASS AND ENERGY BALANCES ON THE WBGT INSTRUMENTATION

A thermodynamic model based on the mass and energy balance equations is hereinafter described in order to evaluate the WBGT index by measuring the four environmental parameters. These balances applied to the natural wet bulb thermometer and the globe one, allow to correlate the above-mentioned parameters to the natural wet bulb and globe temperatures by means of an iterative procedure.

The globe thermometer consists of a Pt100 temperature sensor placed at the centre of a globe made of 0.4 mm copper sheet coated with optically black lacquer (Fig. 1b). The globe has to be a diameter of 0.15 m and a lacquer with an emissivity ε_g equal to 0.98 [2]. Assuming the external surface of the sensor as a control surface (Fig. 1a), the energy balance equation is equal to:

$$\bar{h}_{c,g}\,(t_g - t_a) = \varepsilon_g\,\sigma\,(T_{mr}^4 - T_g^4) + \dot{q}_k \qquad (2)$$

where $\bar{h}_{c,g}$ is the convective heat transfer coefficient, σ is the Stefan-Boltzmann constant and $\dot{q}_k$ is the conductive heat transfer. The influence of the conduction heat transfer along the sensor stem is negligible for low values of d/l_s [7].

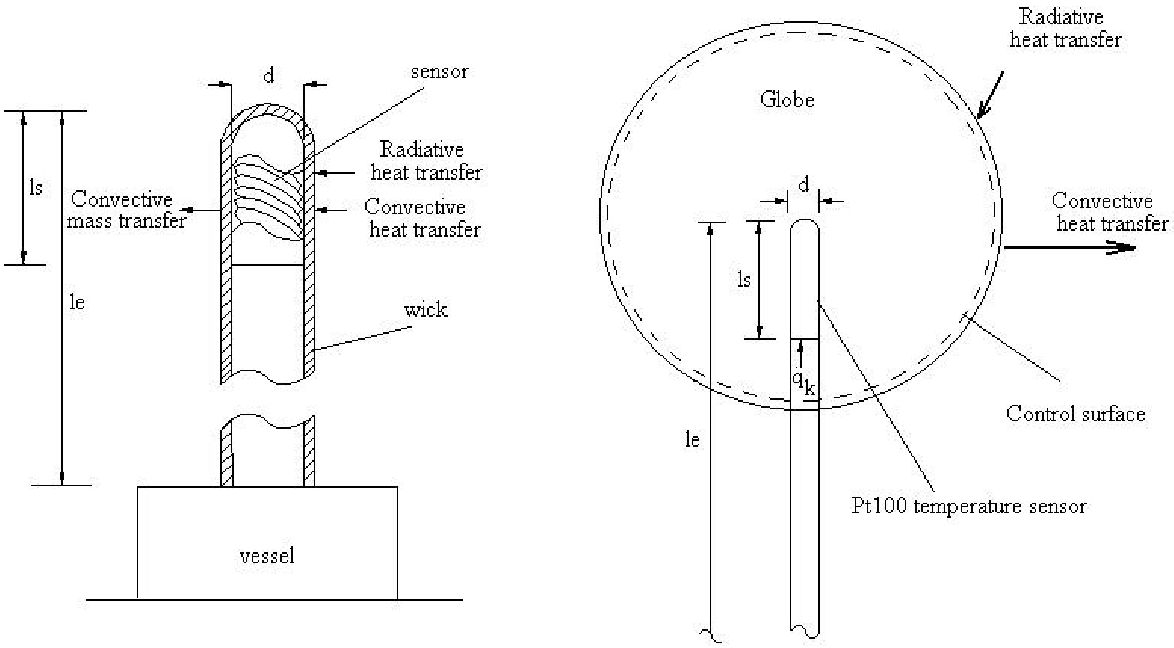

Fig. 1 - Lay out of Wet Bulb Globe Thermometer: a) natural wet bulb thermometer, b) globe thermometer.

To evaluate the convection heat transfer coefficient $\bar{h}_{c,g}$, the McAdams correlation is used [8] with the moist air properties evaluated at the film temperature. As regards the wet bulb thermometer, assuming the external surface of the wick as control surface (Fig. 1a) and neglecting the conduction heat transfer along the sensor stem [7], the energy balance equation becomes:

$$\bar{h}_{c,n}\,(t_a - t_{nw}) + \sigma \cdot \varepsilon_n\,(T_{mr}^4 - T_{nw}^4) = \bar{k}_{c,n} \cdot L\,(w_{nw} - w) \qquad (3)$$

where L is the latent heat of vaporisation and w is the humidity ratio. The convection heat transfer coefficient $\bar{h}_{c,n}$ is obtained applying the McAdams correlation [8]. Therefore, the mass transfer coefficient $\bar{k}_{c,n}$ can be obtained applying the Reynolds analogy [9] to the convection mass exchange.

3 EXPERIMENTAL APPARATUS

In order to generate assigned thermal stress conditions in a confined ambient and, in the mean time, to measure the corresponding WBGT index, an experimental apparatus was opportunely designed and set up at the LAMI (Laboratory of Industrial Measurement – European co-operation for Accreditation laboratory for humidity calibration) in the University of Cassino. It is constituted by (Fig. 2): i) a regulation and control system of the parameters t_a, t_d, v_a, t_{mr}; ii) an apparatus for indirect measure of the WBGT; iii) an apparatus for direct measure of the WBGT.

3.1. Regulation and control system

The experimental plant generates assigned thermal stress conditions (t_a, t_d, v_a, t_{mr}) in a test chamber with a high stability and uniformity (Fig. 2). In particular, the experimental plant allows to regulate: i) the air temperature and humidity by means of a climatic chamber; ii) the air velocity by means of a panel of fans; iii) the mean radiant temperature by means of the thermo-controlled surfaces (by knowing the emissivity value) of the test chamber.

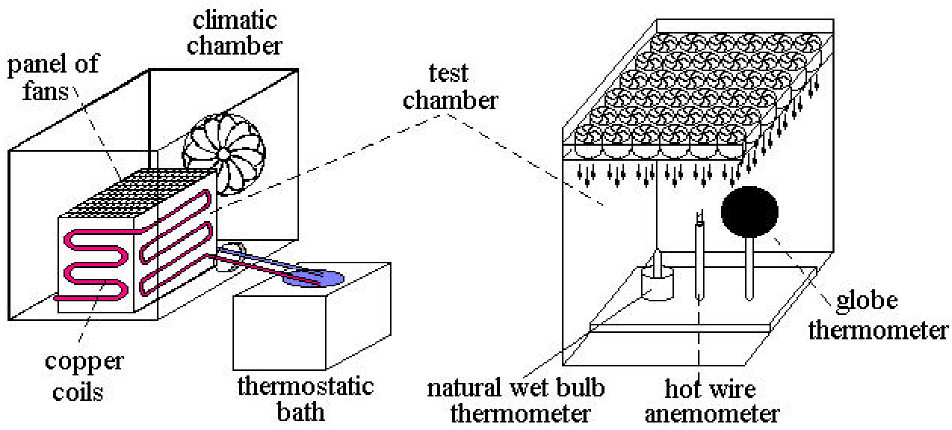

Fig. 2 - Experimental apparatus

The climatic chamber used is a so-called two temperatures generation system, that saturates the air withdrawn from the external environment at an assigned temperature. In this way it is possible to regulate the air humidity. Then, it is introduced in the climatic chamber through an heat exchanger getting to the required thermodynamics conditions by means of a moist air heating. The uniformity and stability in the climatic chamber are equal to 0.1°C for the air temperature in the range between –20 °C and 50 °C and for the dew point temperature in the range between –30 °C and 50 °C [10].

The test chamber has a cubical shape and copper walls covered with Nextel lacquer (emissivity equal to 0.98). The mean radiant temperature can be opportunely regulated in the range 5 ÷ 80 °C by means of copper coils externally welded to every surface of the test chamber and connected to an external thermostatic bath. The external surface of the test chamber is completely insulated with polystyrene panels. The velocity field inside the test chamber is obtained with a panel of fans placed on one side of the test chamber.

The uniformity and stability in the test chamber are equal to: i) 0.15°C for the air temperature, ii) 0.1°C for the dew point temperature, iii) 0.1 °C for the mean radiant temperature and iv) 0.03 m/s for the air velocity.

3.2. Indirect and direct measurements of the WBGT index

The WBGT index can be indirectly evaluated by measuring the air temperature, the air velocity, the humidity and the mean radiant temperature and using eqs. (2) and (3). Therefore, the experimental apparatus is constituted by: i) a dew point hygrometer standard (reference standard of LAMI); ii) a resistance thermometer PT100 to measure the air temperature (calibrated with the reference standard of the LAMI, directly traceable to the IMGC - Istituto di Metrologia "G. Colonnetti" C.N.R. of Turin); iii) a hot wire anemometer to measure the air velocity (calibrated with a pitot tube probe); iv) 20 thermocouples type T tolerance class 1 welded on the internal surfaces of the test chamber to measure the mean radiant temperature (calibrated with the reference standard of the LAMI).

The uncertainty of the above mentioned apparatus is estimated (with a coverage factor k=2), respectively, equal to 0.2°C for the dew point temperature, the air temperature and the mean radiant temperature and to 0.03 m/s for the air velocity.

As regards the apparatus to measure the WBGT index directly, it is constituted by: i) a natural wet bulb thermometer (resistance thermometer Pt100 covered by a wick completely wetted with distilled water); ii) a globe thermometer (a black sphere with a diameter of 0.15 m, containing a Pt100 resistance thermometer). These instrument specifications agree with the ISO 7722 requirements and are calibrated with the reference standard of LAMI. Therefore, the uncertainty of the WBGT direct measurement is estimated equal to 0.25 °C.

4 EXPERIMENTAL AND UNCERTAINTY ANALYSIS

In experimental tests carried out the following ranges are chosen: i) for the air temperature 30-50 °C; ii) for the relative humidity 20-80 % R.H.; iii) for the mean radiant temperature 20-60 °C; iv) for the air velocity 0.1–1.5 m/s.

The velocity field analysed is a steady-state transversal flow. For the measurements carried out, a settling time varying from 1 to 6 hours is considered to obtain thermodynamic equilibrium conditions. In order to calculate the WBGT index applying indirect method, the Sullivan model is used.

The uncertainties, referred to the upper and lower bounds of the ranges considered, are reported in Table I.

Tab. I – Experimental plan and uncertainties

t_a [°C]	ϕ [%R.H.]	t_{mr} [°C]	w [m/s]	$U_{\Delta WBGT}$ [°C]
30	20	20	0.10	± 0.21
			1.50	± 0.21
		60	0.10	± 0.28
			1.50	± 0.21
	80	20	0.10	± 0.23
			1.50	± 0.22
		60	0.10	± 0.28
			1.50	± 0.22
50	20	20	0.10	± 0.27
			1.50	± 0.21
		60	0.10	± 0.26
			1.50	± 0.21
	80	20	0.10	± 0.29
			1.50	± 0.23
		60	0.10	± 0.23
			1.50	± 0.23

Applying the uncertainty propagation laws [11], $U_{\Delta WBGT}$ uncertainties are evaluated. In the ranges considered they are less than 0.3 °C.

In particular, Fig. 3 shows that the WBGT uncertainty: i) slightly depends on the difference between the ambient temperature t_a and the mean radiant temperature t_{mr} and, so, the minimum value is obtained for t_a=t_{mr}, ii) highly depends on the air velocity with the maximum values for low velocities.

As regards the experimental results, in the present paper only some preliminary data are reported. In particular, Fig. 4 shows that the WBGT differences, between the direct and the indirect model, increase as the mean radiant temperature and the air velocity decrease. These errors are one order of magnitude greater than the ones obtained for transversal flow [12]. This is probably due to the Sullivan model that has been obtained for transversal flow and, consequently, the axial flow represents a critical condition. Furthermore, for very low velocities, the natural convection heat and mass transfer (not considered in the Sullivan model) is not negligible.

5 CONCLUSIONS

In the present paper the first experimental results referred to the comparison between direct and indirect methods to evaluate WBGT index for axial flow are reported. The experimental analysis is carried out on the basis of an experimental apparatus designed and made up at the Laboratory of Industrial Measurement in the University of Cassino.

The experimental analysis shows that:

- the Δ_{WBGT} errors decrease as and the air velocity increase. The maximum value found is equal to -3.8°C;
- the influence of the mean radiant temperature on Δ_{WBGT} errors can not be neglected;
- the U_{WBGT} uncertainties seem to have the same trend of the Δ_{WBGT} errors;
- generally the experimental errors are greater than the corresponding uncertainties on WBGT index. For this reason, it is evident that the Sullivan indirect method has to be improved.

Actually the authors are extending the experimental analysis on the WBGT index in different thermodynamic conditions.

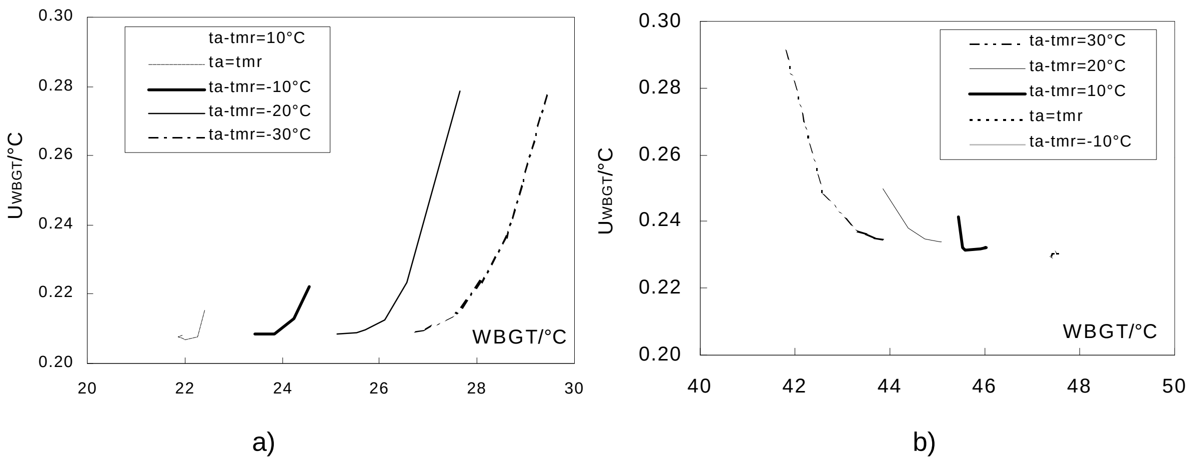

Fig.3 - WBGT uncertainty as WBGT varies for a) t_a=30°C and ϕ=20% and for b) t_a=50°C and ϕ=80%

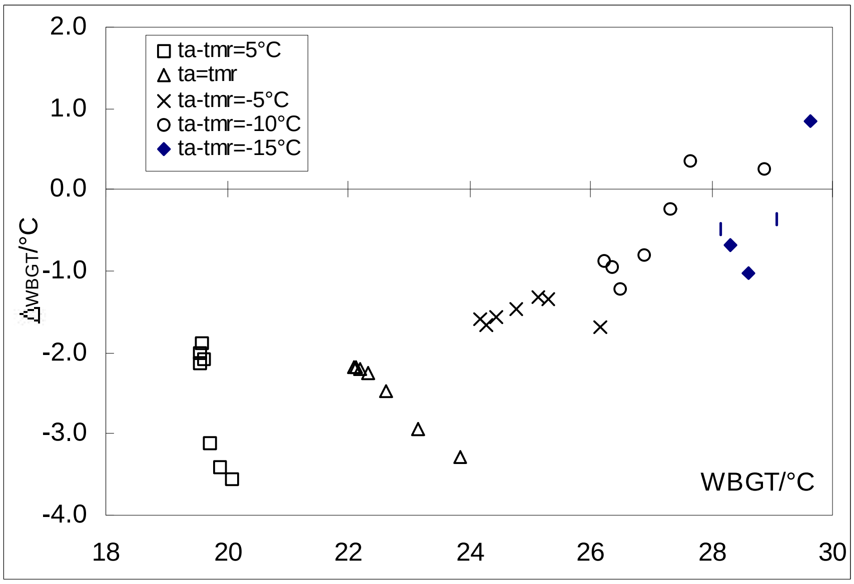

Fig. 4 - WBGT errors as the WBGT varies for t_a=30°C and ϕ=20%

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