A FRIENDLY TOOL FOR THE ASSESSMENT OF THERMAL ENVIRONMENTS

Francesca Romana d'Ambrosio Alfano – fdambrosio@unisa.it (corresponding author)
DIMEC - Dipartimento di Ingegneria Meccanica, Università di Salerno
Via Ponte Don Melillo, 1 – 84084 Fisciano (Salerno) Italy
Boris Igor Palella[1] – palella@unina.it
Giuseppe Riccio[1] – riccio@unina.it
[1]DETEC - Dipartimento di Energetica, Termofluidodinamica Applicata e Condizionamenti Ambientali, Università degli Studi di Napoli Federico II
Piazzale Vincenzo Tecchio 80, 80125 Napoli (Italy)

Abstract. The enhancement of the know-how of the thermal environment has leaded to the formulation of more rational methods for the evaluation of the thermal responses of people. Nevertheless the improvement in human body heat exchange modelling resulted in more complex algorithms making difficult an easy assessment of thermal environments, especially for the beginners. Moreover the assessment interpretation according to the regulations in force is not trivial. Therefore the need of a "friendly" software able to evaluate both thermal comfort and stress indexes improving the life quality and, on the other hand, minimizing the risk of thermal stress pathologies in extreme working conditions, is becoming very urgent.

In this paper an interactive program for the thermal environment assessment is presented. It allows at first to ascertain if the thermal environment is moderate or extreme; moreover, after this preliminary check, it is able to evaluate the whole of thermal indexes. The numeric procedures adopted follow the ISO standard actually in force. The use of this software results in a very easy assessment of the thermal environment for both the ergonomics specialist and the beginner.

Keywords: Thermal comfort, heat stress, cold stress, moderate environments assessment, extreme environments assessment.

1. INTRODUCTION

Beginning from the twentieth century (Houghten and Yaglou, 1923) the thermal sensation evaluation and the characterisation of thermal comfort conditions on a rational basis were plane out for leading only in its second part to the definition of comfort (Fanger, 1970; Gagge, 1971) and stress indexes (Yaglou and Minard, 1957) up till now used. For such reason, depending on the nature of microclimate it became necessary classifying thermal environments in "moderate" and "extreme". In moderate environments the main designer goal is assuring the thermal comfort for the occupants while, in severe ones, protecting the health of workers.

The rational approach for the thermal environment assessment requires:

a. an in-depth physiologic analysis of the human body behaviour in order to predict the subject response to the thermal environment;

b. a detailed analysis of the heat-exchange mechanisms regulating the energy balance of the human body.

In both cases, the right thermal environment assessment needs the implementation of mathematical models often hard to solve, for the experts also. Thus the evaluation of a comfort or stress index also may become a serious problem without a suitable software able to give a fast and clear answer to both the ergonomic specialist and the not skilled technicians.

In the early nineties our research group presented the TEE - Thermal Environment Evaluation - MS-DOS® software (Alfano et al., 1991 and 1992) able to evaluate both sensation indexes for the moderate environments evaluation (PMV and ET*) and stress indexes for extreme ones (WBGT, SW_{req}, IREQ). In the last fifteen years the enhancement of the know-how of the heat exchange mechanisms and the formulation of new physiologic models allowing the prediction of the human body behaviour in unsteady conditions also (d'Ambrosio et al., 1999; Malchaire et al., 2000; Nilsson et al., 2000), resulted in more and more complex models making necessary an often hard regulation update (ISO, 2004a; ISO 2004b; ISO, 2004c). As a consequence, the original version of TEE (now working on Windows® platform) was completely redesigned taking into account not only the working out of new regulations, but especially the need to supply the ergonomic beginner with an evaluation tool as more as possible friendly.

2. THE MAIN TEE INTERFACE

The new version of TEE allows the thermal environment assessment according to the regulations actually in force. More in detail:

- moderate environments: ISO 7730 (ISO, 1994);
- cold extreme thermal environments: ISO TR 11079 (ISO 1993);
- hot extreme thermal environments:
    - ISO 7243 (ISO, 1993)
    - ISO 7933 (ISO, 2004a)
- metabolic rate: ISO 8996 (ISO, 2004d);
- clothing properties: ISO 9920 (ISO, 1995);
- vocabulary and symbols: ISO 13731 (ISO, 2001).

It is noteworthy to bring out that ISO TR 11079, ISO 7730 and ISO 9920 standards, under revision today, are very close to the final passage. A software upgrade is therefore expected within the end of 2005.

At the beginning the computer program uses as input data the standard parameters on which the thermal energy balance of the human body depends (Alfano et al., 1997). Such variables are related to the environment (grouped in microclimatic parameters) and the subject (grouped in subjective parameters).

The program user interface which appears at the program start-up is showed in fig. 1.

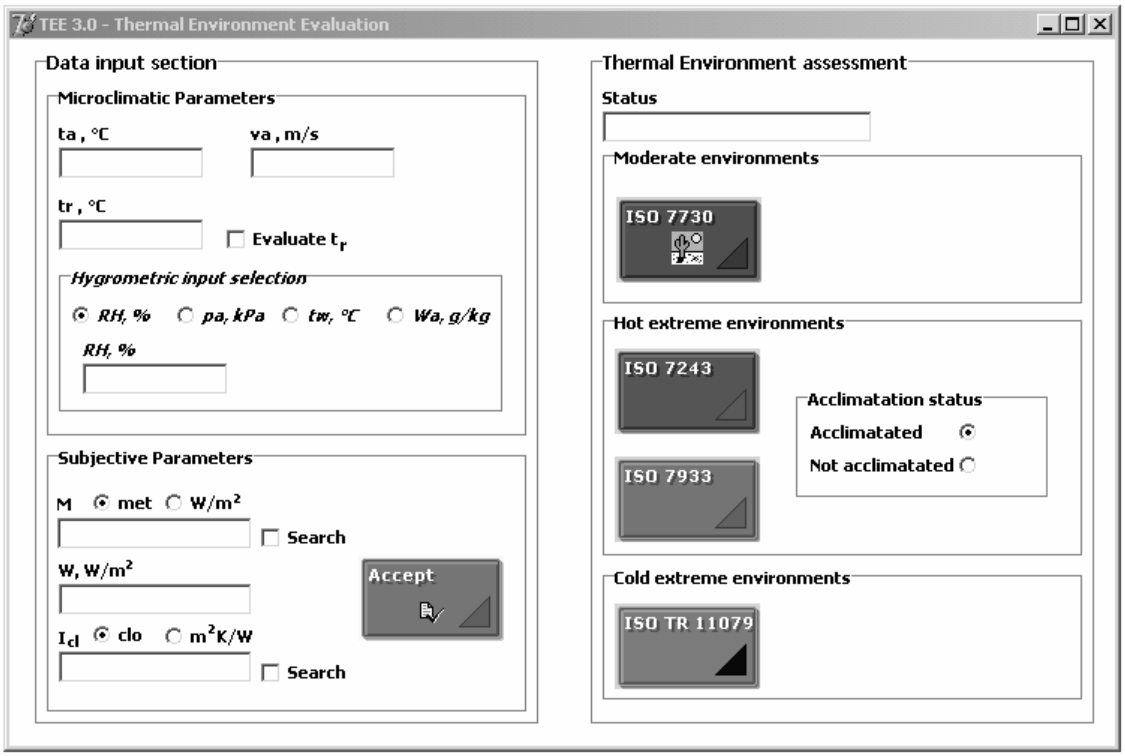

Figure 1 - Main TEE program interface.

The main window program is divided in two sections provided with a series of different boxes:

1. Data input section: devoted to the characterisation of both the microclimate and the subject behaviour.
   Before starting with the thermal environment assessment a set of four microclimatic variables as air temperature (t_a), air absolute velocity (v_a), relative humidity (RH) and the mean radiant temperature (t_r) is required in order to completely characterise the indoor microclimate. Is it possible to have as input data:
   as alternative to the mean radiant temperature: (clicking on the "evaluate t_r" checkbox) the six plane radiant temperatures, t_{pr} (which can be measured through specific probes) or the globe temperature (t_g) according to fig. 2;

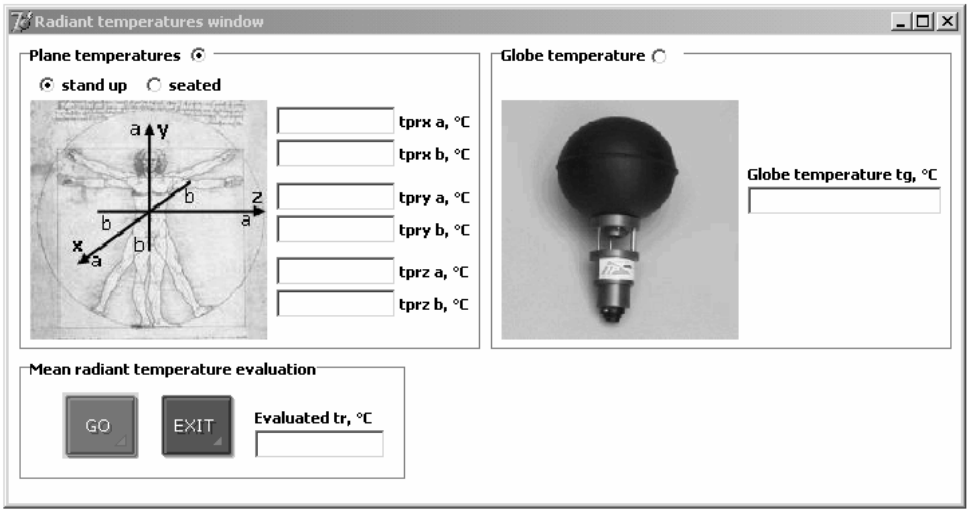

Figure 2 - Mean radiant temperature evaluation window.

as alternative to the relative humidity: the partial pressure of vapour in the air, p_a, the wet bulb temperature, t_w, or the humidity ratio. In case of the values were out of respective ranges an adequate error message appears and the variable is set-up to the maximum allowable value.

It is noteworthy to keep in mind that the evaluation of mean radiant temperature from the plane radiant ones or the globe as well as the evaluation of the relative humidity from wet bulb temperature, partial pressure or humidity ratio, are obtained through the equation reported on the regulation in force (ISO, 1985). Moreover in order to make easier the data input a hint appears when the mouse is moved on the respective variable field.

After the microclimate characterisation the user can define the subjective variables as metabolic rate (M), mechanical work (W) and the static clothing insulation (I_{cl}); concerning such variables input some explanation is required:

Metabolic rate (M): the value of the metabolic rate may be assigned both in met (1 met=58,15 W/m^2) and in W/m^2 by selecting a special checkbox. When a specific value for the requested activity is unknown, the user can look up on the table which appears by clicking on the 'search' checkbox. Each reported value is in accordance to that reported on the regulation in force (ISO, 2004d).

Mechanical work (W): since the human body mechanical efficiency very low (15÷20% at least) mechanical work may be set-up equal to zero; such choice means a safety margin in hot extreme environments assessment (Alfano et al., 1997).

Static clothing insulation (I_{cl}): as above quoted for metabolic rate input, when its value is unknown, the user can look up a right table where both for pre-constituted clothing ensemble and single garments value are reported (ISO, 1995). By this way it is possible to create personalised clothing ensembles just clicking on the search checkbox and selecting one or more fields. I_{cl} value both in m^{2}K/W and in clo (1 clo=0,155 m^{2}K/W) can be assigned.

After data input, by pressing "accept" button, the program loads all variables (preliminary checking the whole of values) and finally suggests the environment type in the status box placed on the top of "ISO 7730" button in order to make easier the right assessment procedure.

2. Thermal environment assessment section: devoted to the thermal environment assessment.

   The first phase of the thermal environment assessment is the evaluation of the PMV index according to ISO 7730 (ISO, 1994): as a matter of fact, only when its value is

known the environment can be assumed moderate or severe. For such reason, both hot and cold extreme environments assessment buttons in fig. 1 are not available before this preliminary operation.

3. MODERATE ENVIRONMENT INTERFACE

Clicking on the respective button the thermal comfort assessment (global and local) window appears (see fig. 3).

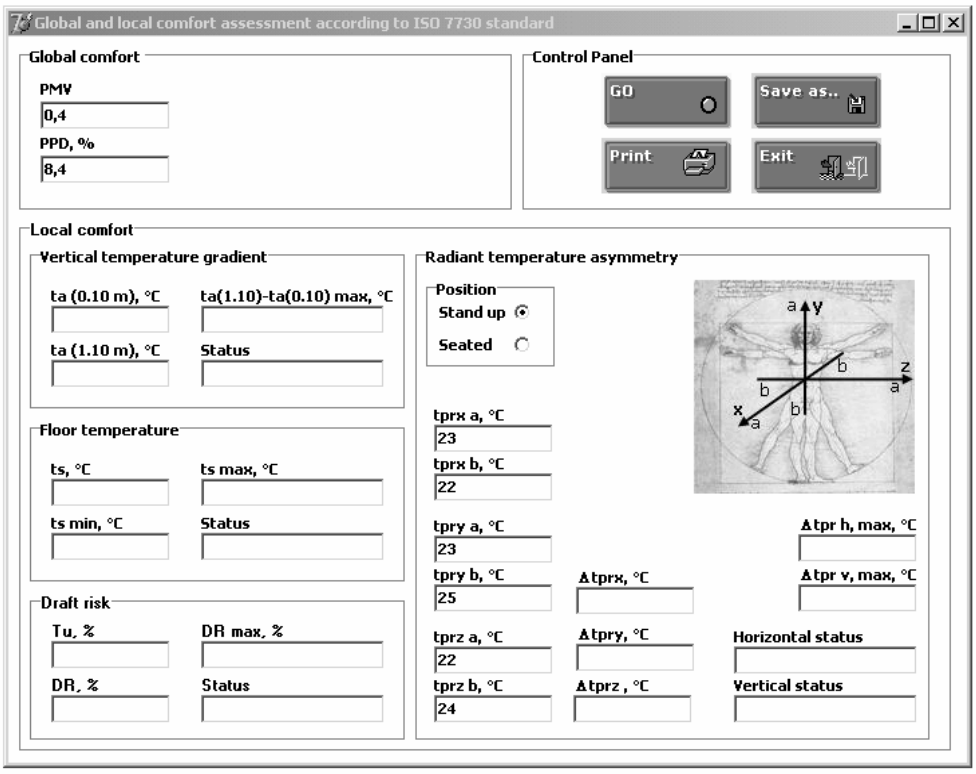

Figure 3 - Moderate environment interface (ISO 7730).

The windows hosts three main boxes:

Global comfort: predicted mean vote (PMV) and the percentage of dissatisfied (PPD) values (calculated according to the data input of fig. 1) here are showed.

1. Local comfort: the user has to put further data related to the causes of local discomfort as:
   - vertical temperature gradient: for its assessment the temperature values measured at 0,10 m and 1,10 m are respectively required;
   - floor temperature: only the floor temperature, t_s, must be input;
   - draft risk: if the absolute air velocity, v_a, value is less than 0,05 m/s or if the air temperature is more than 26°C, the program automatically set up at zero the percentage of dissatisfied corresponding to such local discomfort cause (DR). On the contrary hand, if v_a>0,05 m/s the value of the turbulence intensity, T_u, is required (ISO, 1995). If the user does not provide with an adequate device for its measurement a likely value of 40% may be assumed (Alfano et al., 1997);
   - radiant temperature asymmetry: for its assessment the user, has before to select the right position (stand up or seated) of the subject and then he can put the six values of

plane radiant temperature according to the orientation scheme reported in the box. It is noteworthy remind that if mean radiant temperature is evaluated from plane radiant ones, the user may input neither its values nor the subject position which are automatically set up to the corresponding value of fig. 2.

2. Control panel: is provided with four operation buttons:
   - Go (only for local discomfort evaluation): by clicking on this button the local comfort assessment phase takes place. The user can read the final environment evaluation by checking the message in each status label box.
   - Save as: the program automatically creates a text file with a detailed report.
   - Print: enable the print of the assessment windows.
   - Exit: allows the return to the main window so that user can input new microclimatic data for a new thermal environment evaluation.

4. HOT EXTREME ENVIRONMENTS INTERFACE

In the case of hot severe environment (PMV>1), the software allows two different assessment procedures (see § 3.1) according to the regulation in force:

- wet bulb globe temperature (WBGT) inspiring 7243 standard (ISO, 1993b);
- predicted heat strain (PHS) on which 7933 standard (ISO, 2004a) is based.

4.1. ISO 7243 (WBGT)

A first rough assessment of the thermal environment may be carried out through the evaluation of the WBGT index as ISO 7243 (ISO, 1993b) suggests. By clicking on the "ISO 7243" button a new window appears where the user has to select (fig. 4):

- if the working situation is carried out indoor or outdoor;
- if the environment is uniform or not. In this case a new data-window is opened where the user has to input microclimatic values measured at head, abdomen and ankle level in order to obtain a mean spatial WBGT value;
- if the microclimatic variables are steady or not. According to above quoted the time-average WBGT value is obtained starting from time intervals when each microclimatic variable can be assumed steady. However both microclimatic and time interval values in a special data window may be input.

In the assessment phase only the natural ventilation web bulb temperature, t_{nw}, is required: if unknown, TEE is able to give its value from the other measured microclimatic parameters. A further pressure on the go button result in the evaluation of the WBGT and the subsequent comparison of the limit value imposed by the regulation.

Moreover an easily intelligible sentence expresses if the working has to be stopped or not for the health care of the subject.

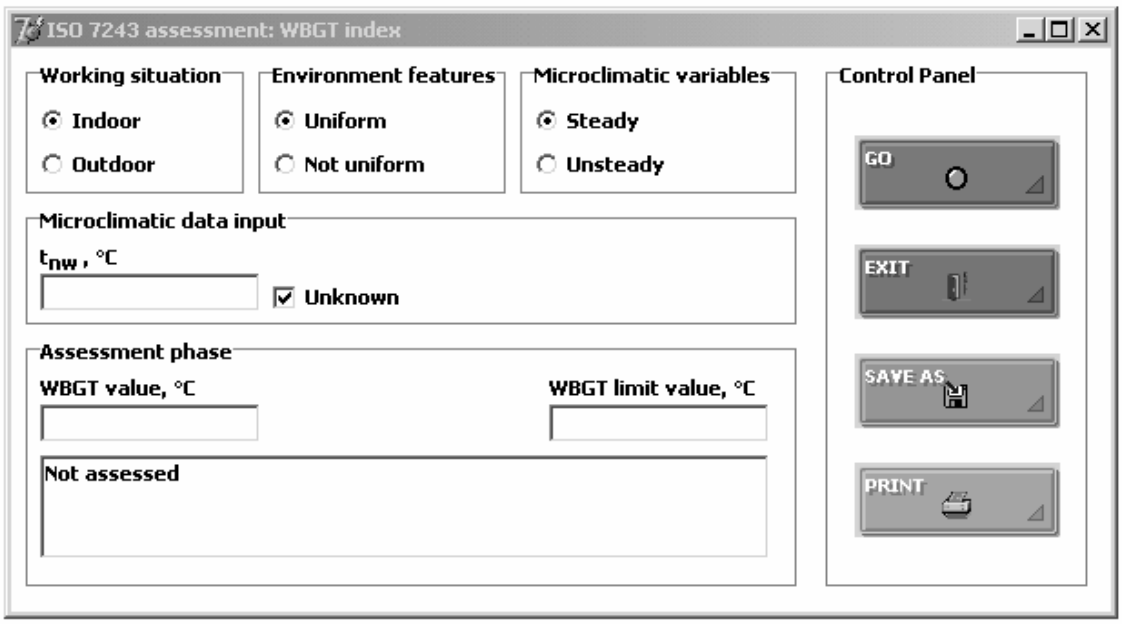

Figure 4 - Hot extreme environments assessment interface (ISO 7243).

4.2. ISO 7933 (PHS method)

By pressing on the "ISO 7933" button (available only if the environment is hot severe) appears on the screen the window depicted in fig. 5. It is composed by three boxes:

1. Additional subjective variables. The user has to input additional information about:
   - position of the subject (stand up, seated or crouched);
   - walking features specifying if the walking direction is unknown or not (and in such case the angle θ between the absolute air speed and the subject is required) or the subject is not walking;
   - clothing additional properties. First of all the static vapour permeability index (i_m) is required. Its typical value is generally 0,38÷0,40, however the program take into account the possibility to check on a right table as above quoted for the static clothing insulation (ISO, 1995).

     According to the ISO 7933 standard when reflective clothing is being worn, the radiant heat exchange coefficient must be corrected by a factor depending on the clothing reflection coefficients (F_r). For such reason the user can input its value if known or check on the table available selecting the search check-box. A typical value 0,97 for F_r, in the case of not reflective clothing, is chosen as default.
2. Control panel: is provided with four operation buttons according to above quoted (see § 3).
3. Assessment results. Concerning the assessment of hot thermal environments through the predicted heat strain method the software returns the whole of final variables as the water loss and the final rectal temperature, t_{re}. Concerning the duration limit exposure:
   - $D_{lim,tre}$ is the maximum allowable exposure time evaluated according to the limitation of the body heat accumulation;
   - $D_{lim,loss50}$ is maximum allowable exposure time for water loss for a mean subject;
   - $D_{lim,loss95}$ is the maximum allowable exposure time for water loss for 95 % of the working population.

   In order to make easier the results reading for beginners also, in the "status" memo-box a "sentence-remark" on the working condition is reported.

   It is noteworthy to point out that the software allows an in-depth analysis also for ergonomic specialist; as a matter of fact, clicking on the "more" button it is possible

reading the whole of variables values that, although essential in the thermal environment assessment, may be ignored by a beginner.

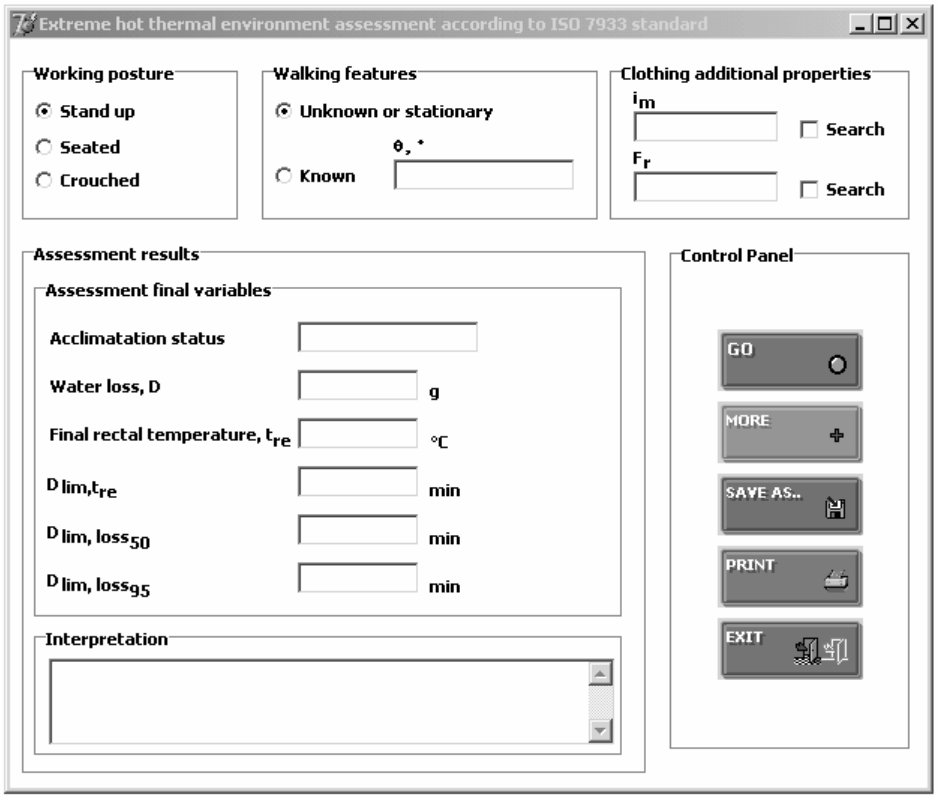

Figure 5 - Hot extreme environments assessment interface (ISO 7933).

5. COLD EXTREME ENVIRONMENTS INTERFACE

Concerning the assessment of the cold extreme environments, any additional variable is required. After clicking on “ISO TR 10079” button a new window program appears (see fig. 6) which exhibits the same structure of hot extreme one. Both general and convective cooling by clicking on “Go” button are carried out. By this way, for general cooling assessment, the software returns minimum and neutral required insulation values ($IREQ_{min}$ and $IREQ_{neutral}$ respectively), the corresponding clothing insulation values ($I_{clr,min}$ and $I_{clr,neutral}$), the duration limits exposure ($D_{lim,min}$ and $D_{lim,neutral}$), and, finally the values of wind chill index (WCI) and the chill temperature, t_{ch}, required for the convective cooling. In the corresponding status memo-boxes a sentence-remark on the working condition is reported.

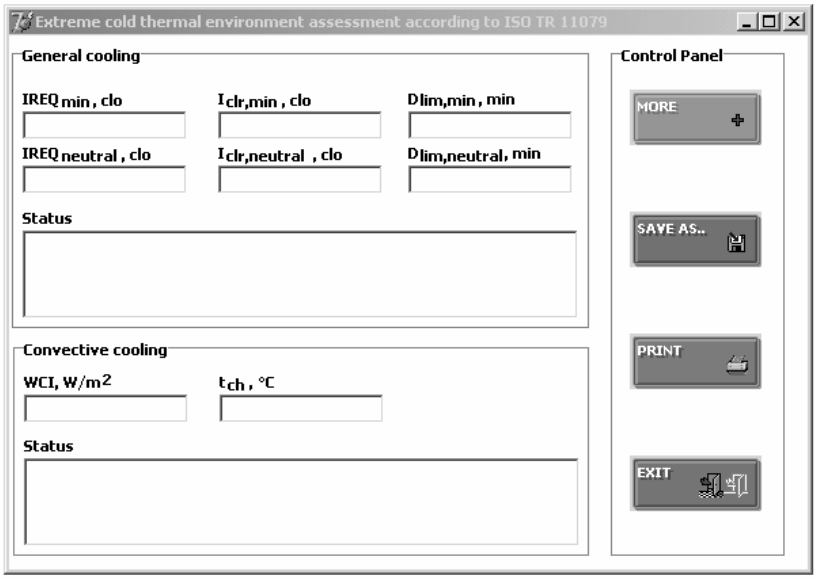

Figure 6 - Cold extreme environments assessment window (ISO TR 11079).

CONCLUSIONS

This paper deals with the Thermal Environment Evaluation – TEE program, designed for the thermal environment assessment. This is the new version of the old TEE software running under MS-DOS® platforms now completely redesigned taking into account the working out of the ergonomic know-how occurred during the last fifteen years. The new graphic interface full of buttons and hints easy to understand supplies both the ergonomic specialist and the beginner with an evaluation tool very friendly to use. The flexibility of its design (carried out in Borland Delphi® 7 language) we will allow in the next future its fast upgrade to the new standard now in discussion (ISO, 2004b; ISO, 2004c; ISO, 2004e). Another version designed for Linux® platforms is under construction also.

REFERENCES

Alfano G. Cesarano G. and d'Ambrosio F. R., 1991, A computer program for thermal environment evaluation, Proceedings of the 11th Congress of the International Ergonomics Association pp. 924-926.

Alfano G., d'Ambrosio F.R., Riccio G., 1992, An evaluation of thermal environments also for non specialist. Proceedings of 5th International Conference on Environmental Ergonomics, Maastricht, pp. 84-85.

Alfano G., d'Ambrosio F. R., Riccio G., 1997, La valutazione delle condizioni termoigrometriche negli ambienti di lavoro: comfort e sicurezza, CUEN, Napoli (Italy)

d'Ambrosio F. R., Lauro E., Alfano G., 1999, Ambienti severi: nuovi criteri di valutazione, CUEN, Napoli (Italy)

Fanger P.O., 1970, Thermal Comfort. New York: McGraw-Hill.

Gagge P.A., Stolwijk J.A.J., Nishi Y., 1971, An effective temperature scale based on a simple model of human physiological regulatory response. ASHRAE Transactions, 77(1), 246-262.

Houghten F.C., e Yaglou C.P. 1923. Determining lines of Equal comfort. ASH&VE Transactions, 28, 361- 384.

ISO, 1985, Thermal environments - Instruments and methods for measuring physical quantities. ISO Standard 7726. Geneva: International Standardization Organization.

ISO, 1993a, Evaluation of cold environments – Determination of required clothing insulation (IREQ). ISO Technical report TR 11079. Geneva: International Standardization Organization.

ISO, 1993b, Hot environments - Estimation of the heat stress on working man, based on WBGT-index (wet bulb globe temperature). ISO Standard 7243. Geneva: International Standardization Organization.

ISO, 1994, Moderate thermal environments - Determination of the PMV and PPD indices and specification of the conditions for thermal comfort. ISO Standard 7730. Geneva: International Standardization Organization.

ISO, 1995, Ergonomics of the thermal environment - Estimation of the thermal insulation and evaporative resistance of a clothing ensemble. ISO Standard 9920. Geneva: International Standardization Organization.

ISO, 2001, Ergonomics of the thermal environment – Vocabulary and symbols. ISO Standard 13731. Geneva: International Standardization Organization.

ISO, 2004a, Ergonomics of the thermal environment – Analytical determination and interpretation of heat stress using calculation of the predicted heat strain. ISO Standard 7933. Geneva: International Standardization Organization.

ISO, 2004b, Ergonomics of the thermal environment - Determination and interpretation of cold stress when using required clothing insulation (IREQ) and local cooling effects. ISO/DIS 11079. Geneva: International Standardization Organization.

ISO. 2004c. Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort. ISO/FDIS 7730. Geneva: International Standardization Organization.

ISO, 2004d, Ergonomics of the thermal environment - Determination of metabolic rate. ISO Standard 8996. Geneva: International Standardization Organization.

ISO, 2004e, Ergonomics of the thermal environment – Estimation of the thermal insulation and evaporative resistance of a clothing ensemble. ISO/CD 9920. Geneva: International Standardization Organization.

Malchaire J., Piette A., Kampmann B., Menhert P., Gebhardt H.J., Havenith G., den Hartog E. , Holmer I., Parsons K., Alfano G., Griefahn B., 2000, Development and validation of the predicted heat strain model, The Annals of Occupational Hygiene, 44.

Nilsson H.O., Anttonen H., Holmér I., 2000, New algorithms for prediction of wind effects on cold protective clothing. Proceedings of NOKOBETEF 6, 1st ECPC, Norra Latin, Stochkolm, 17-20.Yaglou C.P., Minard D., 1957, Control of heat casualties at military training centers. A.M.A. Arch. of Industr. Health, 16, 302-316.