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On the management and prevention of heat stress for crews onboard ships

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ABSTRACT

From the thermo-hygrometrical perspective, some ship compartments are undoubtedly considered severe hot environments due to high temperature values, such as the engine room and, depending on external conditions, cargo holds and storage areas. Such peculiarity further increases already high stress levels related to awkward work postures, lack of space and appropriate lifting tools, noise, vibrations, and a poor air quality. Despite the extensive efforts made by National Governments and International Organizations to improve the quality and the safety of the work on board, over the last several years the thermo-hygrometric characterization of working conditions on board ship seems to have not been investigated enough. Particularly, little monitoring data are available and the use of obsolete or insufficiently validated heat stress indices is a common practice. Addressed to both trained and untrained specialists, this paper discusses how the ergonomic approach of the strategy SOBANE – successfully used for 15 years for risk management and prevention in industrial application – can be implemented on-board. Finally, based on the limited microclimatic data available in the literature, it will be shown which and how heat strain indices should be used for the analysis of heat stress on board.

1. Introduction

1.1. Safety and working conditions onboard

The European Directive 89/391/EEC (Council of the European Community, 1989) devoted to the introduction of measures to encourage improvements in the safety and health of workers at work obliged UE Members to restructure the legislation concerning the organization of health, safety and wellbeing at work. From this perspective, the Italian Law 271/99 (Italian Parliament, 1999) extended to on board ship working environments the general rules valid for any working context in order to provide the maritime industry with efficient legislation covering all the main aspects of work at sea relating to duties and responsibilities (Table 1).

Despite a significant reduction of mortality rates in fatal disasters (Oldenburg et al., 2010), the incidence of accidents in on board work environments is one order of magnitude higher than in land based workplaces (Lu and Tsai, 2008; Oldenburg et al., 2010). Usually, aboard ships there are two different working sites. The first includes all areas generally frequented by the passengers or subjects not involved in technical tasks (or services: cabins, lunchrooms, service zones, etc.). The second are the technical rooms (engine room, auxiliary and machinery areas, rudder and shafts tunnels and so on) where life and working conditions are much harsher with risks higher than other ships areas. This is mainly due to:

1. Work postures: lack of space, and the presence of spare parts and other equipment on steep ladders and slippery surfaces increasing the risk of slip, trips and falls (Jensen et al., 2005). Furthermore, in engine rooms there are many fixed or moving machines and instruments even more dangerous during navigation (e.g. due to vibrations, sudden movements of the ship, etc.).
2. Noise: as described by Kaerlev et al. (2008), hearing problems are common among personnel working in the engine room.
3. Indoor Air Quality (IAQ): although several studies seem to confirm that high ventilation rates effectively reduced the risk of high concentrations of harmful substances (Forsell et al., 2007; Lundh et al., 2011), when tasks were being performed in places with less ventilation, the concentration of oil mist, hydrocarbons and dust exceeded maximum safe limits. This is remarkably often associated with the cleaning of engine parts (Forsell et al., 2007).

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Symbols

BR	boiler room
DLE	maximum allowable exposure time, min
$D_{lim,tre}$	maximum allowable exposure time for heat storage, min
$D_{lim,loss,50}$	maximum allowable exposure time for water loss, mean subject, min
$D_{lim,loss,95}$	maximum allowable exposure time for water loss, 95% of the working population, min
ER	engine room
I_{cl}	basic clothing insulation, $m^2\ K\ W^{-1}$ or clo
$IREQ_{min}$	minimal required clothing insulation, $m^2\ K\ W^{-1}$ or clo
$IREQ_{neu}$	neutral required clothing insulation, $m^2\ K\ W^{-1}$ or clo
M	metabolic rate, $W\ m^{-2}$ or met
p_a	water vapor partial pressure, Pa
PHS	predicted heat strain
PMV	predicted mean vote
PR	pump room
R.H.	relative humidity, %
SW_{TOT}	water loss, g
t_a	air temperature, °C
t_r	mean radiant temperature, °C
t_{re}	rectal temperature, °C
v_a	absolute air velocity, $m\ s^{-1}$
WBGT	wet bulb globe temperature, °C
$WBGT_{lim}$	limit wet bulb globe temperature value for the working situation, °C

Table 1
Main duties and related responsible according to Italian Law 271/99.

Ship owner	Ship owner and captain	Captain
Safety plan editing	Limiting the number of workers onboard exposed to toxic and noxious agents and the duration of the exposure period	Immediate substitution of decaying or deteriorating equipment that could compromise the hygiene and safety of the working environment
Shipping safety plan for the competent maritime Authority	Supplying the Personal Protective Equipment (PPE) to workers and maintaining them in efficient conditions	Conservation and management of the sanitary material onboard
Integration and updating of the safety plan	Providing training and instruction of the Personnel with the help of easy-to-use operative manuals	Preparing instruction for safety procedures for the crew in a clear and comprehensible language
Appointing the Person in charge of the Service of Prevention and Protection	Granting the efficiency of the work environment and the regular maintenance of plants	Warning to the ship owner in case od inadequacies and anomalies observed onboard
Updating the risk assessment	Taking technical and organizational measures in order to contain the risks due to the use of working tools	Appointing, within the crew members, the personnel in charge of prevention measures in case of an emergency
Supply and maintenance of the health care onboard	Supplying adequate instruction of the Safety Delegate	In case of accidents or unpredictable events, he should inform the Ship Owner and the security delegate and take measures to identify and eliminate the causes of the event
Supply of adequate training of the maritime workers	Applying the procedures in the art. 33 – comma 3 in case of changes concerning the work environment conditions	
Compulsory supply of training in case of: (1) Boarding; (2) transfer or change of task; (3) new instrumentations or technologies	Appointing the Personnel in charge of the Prevention and Protection Services	
	Appointing the Doctor	
Recurring refresher courses of training	Organizing the work onboard with the aim of reducing the stress factors to the minimum	
Holding regular meetings on prevention and protection onboard	Informing workers about risks they run while performing their tasks and training them in the use of instrumentation	
	Informing workers on the emergency	
	Getting the workers to respect the hygiene and safety rules	
	Having the workers verify the application of the measures of safety and access to the related information	
	Supplying rules, technical documentation, manuals (see art. 17, guides) (see art. 24 – comma 4) and procedures useful to development of activities in safe conditions to the crew	
	Supplying information to the Service Prevention and Protection on: (1) risk nature; (2) work organization; (3) description of the equipment onboard; (4) data from the "Register of Accidents"	
	Giving adequate information to the workers about: (1) risks for safety and health connected with the navigation; (2) protection measures adopted; (3) specific risks they are exposed to; (4) dangers connected with materials and preparations present onboard; (5) specialist doctor and Responsible of the Prevention Service	
	Limiting the number of workers onboard to be exposed to toxic and noxious agents and the duration of the exposure time	
	Granting the efficiency of the work environment and the regular maintenance of equipment	
	Making technical and organizational measures adequate to contain risk connected with the use of the work equipment	
	Adequate training of the Representative of the Safety	
	Editing an "Register of Accidents"	

4. Heat stress: due to the presence of hot surfaces, engine and boiler rooms reach temperature values higher than external air temperatures (Collins et al., 1971; Ekelin 1977; Orosa and Oliveira, 2010).

1.2. Heat stress onboard

Unlike internal living and service areas (than can be easily equipped with air-conditioning systems) and decks (affected only by the external climate), thermo-hygrometric conditions in technical spaces such as engine rooms (ER) are affected by the external climate, the ventilation and the heat given off by the engine components such as heat exchangers, pipes, cooling, and fuel preheaters, through convection and radiation (Ekelin, 1977). This occurrence results in air temperature values from 10 °C to 20 °C higher than the external temperature (Collins et al., 1971; Ekelin, 1977). Consequently, the thermo-hygrometric conditions in the engine room can be extremely dangerous during the hot season.

Even in the recent past, several surveys which have been devoted to the characterization of working conditions on board ships (Jensen et al., 2006; Lundh et al., 2011) have shown that the engine crew suffer the highest overall levels of stress followed by the deck and engine officers (Elo, 1985) especially because of the higher levels of heat stress (Oldenburg et al., 2009). Moreover, although it is widely accepted that the ER is a very hazardous environment, the interest of researchers in the field has been mainly focused on the identification of the main risk factors to be taken into account at the design and management level (NAVMED, 1988; Lundh et al., 2011) rather than on systematic studies devoted to the thermo-hygrometric characterization of such special work environments. From this perspective, we must raise three main criticisms:

1. Contrary to the common practice in industrial workplaces (Parsons, 2008; d'Ambrosio Alfano et al., 2014), both risks analysis and prevention measurements with respect to heat stress are not usually approached from an ergonomic perspective (Malchaire et al., 1999; Lundh et al., 2011) that requires the integration of instrumental analyses with subjective investigations (e.g. administration of checklists and/or self-reporting questionnaires). This is because crews are comprised not only of many different nationalities but also of members from different cultural backgrounds with different expectation levels (Oldenburg et al., 2010).
2. Very little data of microclimatic monitoring is available. According to Table 2, all data refers to specific routes during only one season and on specific ships (Collins et al., 1971; Orosa and Oliveira, 2010). Moreover, in only one case have all physical variables affecting the thermal sensation (air temperature, air velocity, relative humidity, mean radiant temperature) been measured (Collins, 1971). This lack of information is obviously due to the difficulty in measuring all parameters without interfering in the operations of crews within the technical spaces. Last but not least, no medical surveys focusing on the evaluation in the field of the main indicators of heat strain (e.g., rectal temperature, water loss, skin wettedeness) can be found in the literature.
3. The assessment of heat stress conditions is usually carried out by means of empirical indices like WBGT (Collins et al., 1971; Ekelin, 1977; NAVMED, 1988) that can only be used when light clothing is worn (d'Ambrosio Alfano et al., 2011). Furthermore, more robust strain predictors such as the PHS model (Malchaire et al., 2001; 2002; ISO, 2004a, 2004b) are ignored even by occupational health professionals who prefer out of date and unreliable indices (Orosa and Oliveira, 2010).

In order to provide both trained and untrained occupational health professionals useful information about the ergonomic approach in dealing with on board heat stress, this paper will discuss how the principles of the SOBANE strategy (Malchaire et al., 1999) – successfully implemented for 15 years for risk management and prevention in industrial applications – must be adopted to assess and manage this issue in critical ship areas.

To this end, based on the limited microclimatic data available in the literature, it will be shown how and which heat strain indices must be used for the thermo-hygrometric analysis of working conditions.

2. Heat stress management for industrial environments: the strategy SOBANE

2.1. Introduction

European policies in the field of the safety and health of workers resulted in the formulation of a special strategy called SOBANE, developed by Malchaire et al. (1999) presently validated in 14 fields (social facilities, safety, machines and hand tools, electricity, fire and explosion, lighting, work on video display units, noise, thermal environment, chemical agents, biological agents, musculoskeletal disorders, vibrations transmitted to the hand–arm and the whole body) as reported in Malchaire and

Table 2
Summary of main thermo-hygrometrical surveys on-board from literature. BR=boiler room; CR=Control Room; ER=Engine Room; PR=Pump Room. * Calculated according to ISO 7726 Standard (ISO, 1998).

REF.	SEASON and ROUTE	SHIP	PLACE		t_a (°C)	RH (%)	t_w (°C)	t_r (°C)	t_g (°C)	v_a (m/s)
Orosa and Oliveira	Mediterranean coast of Spain in winter	Merchant ship	ER	MIN	25.4	16.2	–	–	–	–
				MAX	38.5	33.9				
				AVG	32.5	24.9				
			CR	MIN	17.4	30.3	–	–	–	–
				MAX	27.3	70.5				
				AVG	19.8	41.2				
Collins et al.	Persic Gulf in summer	Oil tanker	BR	MIN	45.8	26.0*	27.8	50.6*	49.2	0.03
				MAX	65.0	25.0*	41.0	73.3*	70.0	0.25
				AVG	–	–	–	–	–	–
			ER	MIN	44.2	46.2*	32.8	50.5*	47.0	0.5
				MAX	45.8	41.6*	32.8	60.2*	51.0	1.0
				AVG	–	–	–	–	–	–
			PR	MIN	39.2	64.6*	31.7	44.7*	43.0	0.08
				MAX	42.0	64.5*	35.3	40.4*	41.1	0.18
				AVG	–	–	–	–	–	–

Table 3
Peculiarities of the four levels forming the base of SOBANE strategy (Malchaire et al., 1999).

	Screening	*Observation*	*Analysis*	*Expertize*
When?	Systematically	When a problem is detected	More complicated cases	Very complex cases
How?	Opinions	Qualitative observations	Ordinary measurements	Specialized Measurements
Costs?	Very low	Low	Average	High
Duration (order of magnitude)	10 min	2 h	1 day	A few days
By whom	Workers and management form the company	Workers and management form the company	Same + specialists	Same + specialists and experts
Knowledge				
Working conditions	Very high	High	Average	Low
Ergonomics	Low	Average	High	Specialized

Piette (2006). SOBANE strategy attributes less importance to the recognition phase of the problem focusing instead on the search for solutions. It seeks to organize efficiently, economically and durably the efforts of the various partners of health and safety at work: employees, hierarchy, occupational health and safety practitioners and experts. SOBANE strategy is organized in four levels: (1) Screening; (2) Observation; (3) Analysis; (4) Expertize, according to Table 3.

2.2. *SOBANE strategy in the field of the thermal environment*

In the field of thermal environments, some SOBANE's principles were adopted by the ISO Standard 15265 (ISO, 2004b) which describes a strategy for assessing and interpreting the risk of physiological constraints, or of discomfort, while working in a given climatic environment. Such a Standard provides for a protocol of investigation characterized by a thorough analysis of the working conditions aimed at identifying quick solutions for easy problems or requiring special investigations in complex situations. Therefore, the main goal is not the quantification of the risks but rather their prevention, elimination or reduction. ISO 15265 is structured in three stages:

a) Observation. This requires only a preliminary collection of information about the work situation, in general concerning the working conditions, the climatic conditions and the heat or cold sources. The air temperature can be measured while the others variables responsible for the physiological response of the human body to the microclimate (mean radiant temperature, air velocity, relative humidity, metabolic rate and clothing properties) have to only be estimated. Moreover, it prescribes taking into account the workers' judgment measured on mono- or bi-polar scales, where the zero score characterizes the optimal situation (Table 4). The number of preventive and controlling actions to be implemented (e.g. a changing of the clothing, a shielding of the radiant surfaces and so on) is strictly related to the deviation with respect to zero (in principle the range of acceptability is in the range from −1 to +1 on a bi-polar scale). In any case, if the controlling actions were not sufficient or their implementation did not lead to foreseeable results, a further step of analysis is needed.
b) Analysis. This stage is based on a three-step investigation. (i) An analysis of the sequence of activities carried out in the workplace and some thermal comfort aspects is primarily required. In particular the factors that should be taken into account are possible rises or falls of air temperature, differences in relative indoor–outdoor humidity, the direct solar radiation, hot and cold surfaces, draughts and, finally, workload and clothing characteristics especially if protective clothing is required. (ii) An assessment of the working situation and a calculation of the main indices (Malchaire et al., 1999). (iii) A risk assessment based on the values of the indices previously calculated.

The assessment of the class of risk in the analysis step is based on the calculation of the PMV index (ISO, 2005) and the application of PHS (ISO, 2004a) and IREQ (ISO, 2007a) models

Table 4
Scoring scales for the Observation level (ISO, 2004b).

Score	**Condition**
Air temperature	
−3	Generally freezing
−2	Generally between 0 °C and 10 °C
−1	Generally between 10 °C and 18 °C
0	Generally between 18 °C and 25 °C
1	Generally between 25 °C and 32 °C
2	Generally between 32 °C and 40 °C
3	Generally greater than 40 °C
Humidity	
−1	Dry throat/eyes after 2–3 h
0	Normal
1	Moist skin
2	Skin completely wet
Thermal radiation	
−1	Cold on the face after 2–3 min
0	No radiation discernible
1	Warm on the face after 2–3 min
2	Unbearable on the face after more than 2 min
3	Immediate burning sensation
Air movements	
−2	Cold strong air movements
−1	Cold light air movements
0	No air movements
1	Warm light air movements
2	Warm strong air movements
Physical work load	
0	Office work: easy, low muscular constraints, occasional movements at normal speed
1	Moderate work with arms or legs: use of heavy machines, steadily walking
2	Intense work with arms and trunk: handling of heavy objects, shoveling, wood cutting, walking rapidly or while carrying a heavy load
3	Very intense work at high speed: stairs, ladders
Clothing	
0	Light, flexible, not interfering with the work
1	Long, heavier, interfering slightly with the work
2	Clumsy, heavy, special for radiation, humidity or cold temperatures
3	Special overalls with gloves, hoods, shoes
Opinions of the workers	
−3	Shivering, strong discomfort for the whole body
−2	Strong local discomfort; overall sensation of coolness
−1	Slight local cool discomfort
0	No discomfort
1	Slight sweating and discomfort; thirst
2	Heavy sweating, strong thirst, work pace modified
3	Excessive sweating, very tiring work, special clothing

(in case of hot and cold, respectively) to obtain the maximum allowable exposure time (DLE) as showed in Table 5.
Finally, after the identification of the preventive and short-term controlling actions, the real situation has to be compared with the predicted one in order to assess the residual risk and to define protective and medical survey actions to be implemented. In this case the six variables responsible for the physiological response of the human body must be estimated (in case of personal parameters by means of tables reported in Standards) by common technicians.

c) Expertize. This further step is required if the analysis stage does not lead to the solution. In particular, it is aimed at quantifying, analyzing and assessing the risks in attempting to solve all the unsolved situations recognized in the previous stages. To this end, specially skilled personnel and the use of sophisticated measurement techniques are required. This stage also requires a preliminary selection of the situations to be expanded, the data collection under average and extreme conditions and the calculation of the indices. Finally, it requires the definition of the preventive and controlling actions, the selection of the modifications to be implemented (e.g. microclimatic parameters, work organization and so on), the assessment of the residual risks and, eventually, the choice of the measures of personal protection and medical survey to be adopted.

3. Heat stress indices calculation at analysis level according to ISO 15265 Standard

3.1. Input data

In order to provide specific details on the best practice for carrying out the thermo-hygrometrical analysis of mostly technical spaces on board such as the engine room (or boiler and pump rooms), we will discuss two case studies based on the little data available in the literature (see Table 2) taking special care in the calculation of which indices should be used.

The analysis of the working conditions has been carried out by calculating all required indices according to ISO 15265 Standard (ISO, 2004b; d'Ambrosio Alfano et al., 2013a) as showed in Table 5.

Particularly, PHS model (ISO, 2004a) was used for the quantitative assessment of heat strain in terms of the main physiological variables (predicted rectal temperature and water loss) and the duration limit of the exposure.

Numerical simulations were performed using Thermal Environment Evaluation (TEE) package (d'Ambrosio Alfano et al., 2007) – a special software used for assessing the Thermal Environment in accordance with all International Standards pertaining to the Ergonomics of the Thermal Environment. Personal and microclimatic data have been established as follows:

- Personal data. Concerning the metabolic rate, the investigation was conducted in the range between low and moderate activities according to ISO 8996 (ISO, 2004c). In particular, the mean value for low activity (180 W), the transition value between low and moderate (235 W) and the mean value for moderate activity (295 W), were studied, in accordance with the classification summarized in Table 6. The calculation of the basic clothing thermal insulation (ISO, 2007b) was carried out according to ISO 7933 Standard (ISO, 2004a) based on the single garments most likely worn by crews in ER compartments and was settled at $I_{cl}=1{,}0$ clo (Table 7).
- Microclimatic data. Numerical processing was carried out by using as input data the little microclimatic data available in the literature summarized in Table 2. Please observe that in the case of the merchant ship, the authors did not measure either the mean radiant temperature or the air velocity values. Consequently, these two quantities were settled according to the survey carried out by Collins et al. (1971). In particular, as far as the mean radiant temperature was concerned (ISO, 1998), both were calculated under uniform conditions ($t_r=t_a$) and imposing

Table 5
Classes of risk reported in ISO 15265 standard (ISO, 2004b).

Class	Criteria
Immediate constraint	$D_{lim} < 30$ min
Constraint in the short term	$I_{clr} < IREQ_{min}$ DLE < 120 min
Constraint in the long term	$PMV < -2$ $IREQ_{min} \le I_{clr} \le IREQ_{neutral}$
Cold discomfort	$-2 \le PMV < -0.5$
Comfort	$-0.5 \le PMV \le +0.5$
Warm discomfort	$+0.5 < PMV \le +2$
Constraint in the long term[a]	$D_{lim} < 480$ min
Constraint in the short term[a]	$D_{lim} < 120$ min
Immediate constraint[a]	$D_{lim} < 30$ min

[a] in these situations the water loss for 8 h of continuous work and the predicted risk of increase of the internal temperature of the body according to ISO 7933 standard are required.

Table 7
Basic clothing insulation values for some garment ensembles (ISO, 2004a).

Garment ensembles	I_{cl} (clo)
Briefs, short-sleeve shirt, fitted trousers, calf length socks, shoes	0.5
Underpants, shirt, fitted trousers, socks, shoes	0.6
Underpants, coverall, socks, shoes	0.7
Underpants, shirt, coverall, socks, shoes	0.8
Underpants, shirt, trousers, smock, socks, shoes	0.9
Briefs, undershirt, underpants, shirt, overalls, calf length socks, shoes	1.0

Table 6
Classification of metabolic rate by value and category (ISO, 2004c).

Class	Average metabolic rate (W)	Examples
0 Resting	115 (100–125)	Resting
1 Low metabolic rate	180 (125–235)	Sitting at ease: light manual work (writing, typing, drawing, sewing, book-keeping); hand and arm work (small bench tools, inspection, assembly or sorting of light materials); arm and leg work (driving vehicle in normal conditions, operating foot switch or pedal).
2 Moderate metabolic rate	295 (360–465)	Sustained hand and arm work (hammering in nails, filing); arm and leg work; arm and trunk work (work with pneumatic hammer, tractor assembly, plastering, intermittent handling of moderately heavy material, weeding, hoeing, picking fruits or vegetables, pushing or pulling light-weight carts or wheelbarrows, walking at a speed of 3.5–5.5 km/h, forging).
3 High metabolic rate	415 (360–465)	Intense arm and trunk work; carrying heavy material; shovelling; sledgehammer work; sawing; planning or chiselling hard wood; hand mowing; digging; walking at a speed of 5.5–7 km/h. Pushing or pulling heavily loaded hand carts or wheelbarrows; chipping castings; concrete block laying.
4 Very high metabolic rate	520 (> 465)	Very intense activity at fast to maximum pace; working with an axe; intense shovelling or digging; climbing stairs, ramp or ladder; walking quickly with small steps; running; walking at a speed greater than 7 km/h.

Table 8a
Heat stress analysis of a merchant ship in winter season (Orosa and Oliveira, 2010). In bold letters the table shows microclimatic conditions requiring the limitation of the work shift for excessive water loss or rectal temperature reaching 38 °C. I_{cl}=1.0 clo; v_a=0.1 m s^{-1}; acclimatized crews.

$t_r=t_a$ (°C)	RH (%)	*M* (W)	**PMV (–)**	WBGT (°C)	SWTOT (g)	t_{re} (°C)	$D_{lim,loss,95}$ (min)	$D_{lim,tre}$ (min)	DLE (min)
25.4	16.2	180	0.85	17.1	1524	37.3	480	480	480
		235	1.19	17.1	2249	37.4	480	480	480
		295	1.67	17.1	3187	37.6	480	480	480
	24.9	180	0.90	18.1	1532	37.3	480	480	480
		235	1.23	18.1	2277	37.4	480	480	480
		295	1.71	18.1	3254	37.6	480	480	480
	33.9	180	0.95	19.2	1544	37.3	480	480	480
		235	1.28	19.2	2317	37.4	480	480	480
		295	1.76	19.2	3345	37.6	480	480	480
32.5	16.2	180	2.13	22.4	2468	37.3	480	480	480
		235	2.39	22.4	3405	37.4	480	480	480
		295	2.90	22.4	**4620**	37.6	393	480	393
	24.9	180	2.20	23.7	2568	37.3	480	480	480
		235	2.46	23.7	3607	37.4	480	480	480
		295	2.97	23.7	**4989**	37.6	365	480	365
	33.9	180	2.28	25.0	2729	37.3	480	480	480
		235	2.53	25.0	**3945**	37.4	458	480	458
		295	> 3	25.0	**5632**	37.5	325	480	325
38.5	16.2	180	2.13	26.8	**3755**	37.3	480	480	480
		235	2.39	26.8	**5076**	37.4	359	480	359
		295	2.90	26.8	**6783**	37.6	273	480	273
	24.9	180	> 3	28.4	**4393**	37.2	412	480	412
		235		28.4	**6254**	37.4	294	480	294
		295		28.4	**7369**	**38.6**	251	180	180
	33.9	180		**30.0**	**5543**	**38.1**	322	358	322
		235		**30.0**	**7042**	**39.4**	256	120	120
		295		**30.0**	**7374**	**40.7**	250	69	69

Table 8b
Heat stress analysis of a merchant ship in winter season (Orosa and Oliveira, 2010). In bold letters the table shows microclimatic conditions requiring the limitation of the work shift for excessive water loss or rectal temperature reaching 38 °C. I_{cl}=1.0 clo; v_a=1.0 m s^{-1}; acclimatized crews.

$t_r=t_a$ (°C)	RH (%)	*M* (W)	**PMV (–)**	WBGT (°C)	SWTOT (g)	t_{re} (°C)	$D_{lim,loss,95}$ (min)	$D_{lim,tre}$ (min)	DLE (min)
25.4	16.2	180	0.54	16.1	1183	37.3	480	480	480
		235	0.97	16.1	1780	37.4	480	480	480
		295	1.50	16.1	2511	37.6	480	480	480
	24.9	180	0.58	17.3	1177	37.3	480	480	480
		235	1.01	17.3	1777	37.4	480	480	480
		295	1.55	17.3	2513	37.6	480	480	480
	33.9	180	0.64	18.5	1172	37.3	480	480	480
		235	1.06	18.5	1774	37.4	480	480	480
		295	1.60	18.5	2517	37.6	480	480	480
32.5	16.2	180	2.11	21.3	2131	37.3	480	480	480
		235	2.40	21.3	2805	37.5	480	480	480
		295	2.94	21.3	3628	37.7	480	480	480
	24.9	180	2.18	22.8	2139	37.3	480	480	480
		235	2.47	22.8	2827	37.5	480	480	480
		295	> 3	22.8	3671	37.7	480	480	480
	33.9	180	2.26	24.3	2155	37.3	480	480	480
		235	2.54	24.3	2864	37.5	480	480	480
		295	> 3	24.3	3738	37.6	480	480	480
38.5	16.2	180	2.11	25.7	3060	37.4	480	480	480
		235	2.40	25.7	**3824**	37.6	471	480	471
		295	2.94	25.7	**4751**	37.7	382	480	382
	24.9	180	> 3	27.5	3144	37.4	480	480	480
		235		27.5	**3957**	37.5	456	480	456
		295		27.5	**4948**	37.7	367	480	367
	33.9	180		29.2	3310	37.4	480	480	480
		235		29.2	**4215**	37.5	429	480	429
		295		29.2	**5327**	37.7	342	480	342

$t_r - t_a$ values ranging from 5 to 15 °C (see Table 2 in case of ER). Finally, air velocity values were settled consistently with still air (0.1 m s^{-1}) and forced air conditions (1.0 m s^{-1}) as reported by Collins et *al.* (1971). This value is also consistent with US Navy Naval Medical Command recommendations (NAVMED, 1998) that reports some design values for air velocity in the range 0.8–1.3 m s^{-1} for 4–8 h exposures in propulsion spaces.

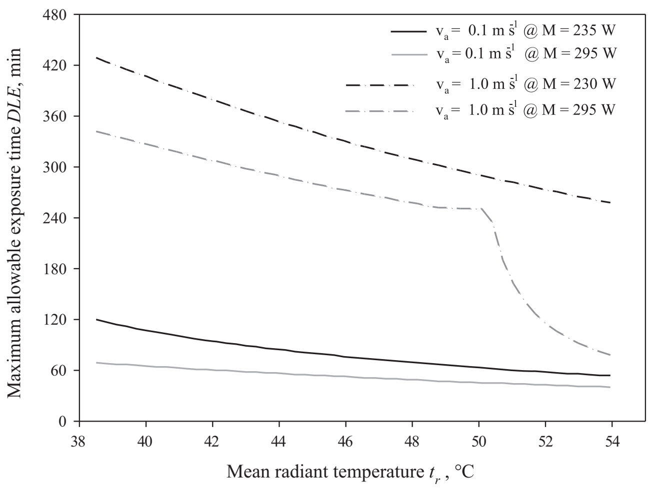

Fig. 1. Effect of the mean radiant temperature on the maximum allowable exposure times in ER compartment. I_{cl} = 1.0 clo, t_a = 38.5 °C, RH = 33.9%, acclimatized crews.

Table 9
WBGT limit values recommended by ISO 7243 Standard (ISO, 1989).

Metabolic rate class	Metabolic rate, MW	Reference WBGT limit value ($WBGT_{lim}$), °C			
		Person acclimatized to heat		Person not acclimatized to heat	
0 (Resting)	100–125	33		32	
1	125–235	30		29	
2	235–360	28		26	
		No sensible air movement	Sensible air movement	No sensible air movement	Sensible air movement
3	360–465	25	26	22	23
4	$M > 465$	23	25	18	20

3.2. *Case of study 1: merchant ship in winter*

Tables 8a and 8b summarize the results of the analyses of working conditions according to the ISO 15265 Standard (see Table 4) based on microclimatic values reported in Table 2. In order to highlight the reason why empirical indices can only be used for a rough assessment of heat stress (ISO, 1989; d'Ambrosio Alfano et al., 2014) the values of WBGT index have been also calculated (see Table 8 for limit values recommended by ISO 7243 Standard).

On the basis of obtained results we can observe that:

- Empirical indices as WBGT systematically underestimate heat strain expected levels especially under still air conditions (v_a = 0.1 m s^{-1}). Particularly, on 18 microclimatic conditions inconsistent with a continuous 8 h shift, in only 3 situations does WBGT reach the limit values recommended by ISO 7243 Standard (at high air temperature and low air velocity, as pointed out in Table 8a).
- Due to the increase of heat transfer by convection and evaporation, some ventilation contributes to the reduction of heat strain (this usually occurs during navigation when engines requires high air intakes). In fact, according to Table 8b, in only four cases should the shift be interrupted before 480 min due to the risk of de-hydration. On the contrary, most critical conditions are encountered at low air velocity (e.g. during repairs when engines are turned off): in this case DLEs values can drop up to about an hour (69 min) due to excessive rectal temperature. In particular, as showed in Table 8a, at high air temperature and humidity values predicted rectal temperature exceeds the limit values of 38 °C.
- From the physiological perspective, it is very important to observe that, apart from high humidity and low air velocity conditions, when sweat does not evaporate and drips from the body, in most cases the limitation of the shift duration is due to the risk of dehydration. This means that the adequate administration of liquids to the crews during long durations (e.g. emergency repairs) is a must for both safety and health when exposed to such extreme conditions. However, ISO 7933 Standard accounts for the impossibility of rehydration by reducing from 5%

Table 10
Heat stress analysis of an oil tank in summer season (Collins et al., 1971). In bold letters the table shows microclimatic conditions requiring the limitation of the work shift for excessive water loss or rectal temperature reaching 38 °C. I_{cl} = 1.0 clo; acclimatized crews.

Place	t_a (°C)	t_r (°C)	v_a (m s^{-1})	RH (%)	M (W)	PMV (–)	WBGT (°C)	SWTOT (g)	t_{re} (°C)	$D_{lim,loss,95}$ (min)	$D_{lim,tre}$ (min)	DLE (min)
BR	45.8	50.6	0.03	26.0	180	> 3	**36.9**	**7198**	**43.6**	255	51	51
					235		**36.9**	**7244**	**44.8**	253	41	41
					295		**36.9**	**7397**	**46.4**	248	33	33
	65.0	73.3	0.25	25.0	180		**50.8**	**7105**	**59.2**	258	17	17
					235		**50.8**	**7122**	**60.9**	258	15	15
					295		**50.8**	**7243**	**63.0**	254	14	14
ER	44.2	50.5	0.5	46.2	180		**37.6**	**7140**	**44.7**	257	37	37
					235		**37.6**	**7169**	**45.6**	256	31	31
					295		**37.6**	**7302**	**47.0**	252	26	26
	45.8	60.2	1.0	41.6	180		**38.9**	**7146**	**43.0**	257	38	38
					235		**38.9**	**7176**	**44.3**	256	32	32
					295		**38.9**	**7311**	**46.1**	251	26	26
PR	39.2	44.7	0.08	64.6	180		**36.7**	**7122**	**46.8**	258	36	36
					235		**36.7**	**7145**	**48.3**	257	30	30
					295		**36.7**	**7272**	**49.8**	253	25	25
	42.0	40.4	0.18	64.5	180		**37.2**	**7100**	**48.1**	258	31	31
					235		**37.2**	**7119**	**49.6**	258	26	26
					295		**37.2**	**7239**	**51.0**	254	22	22

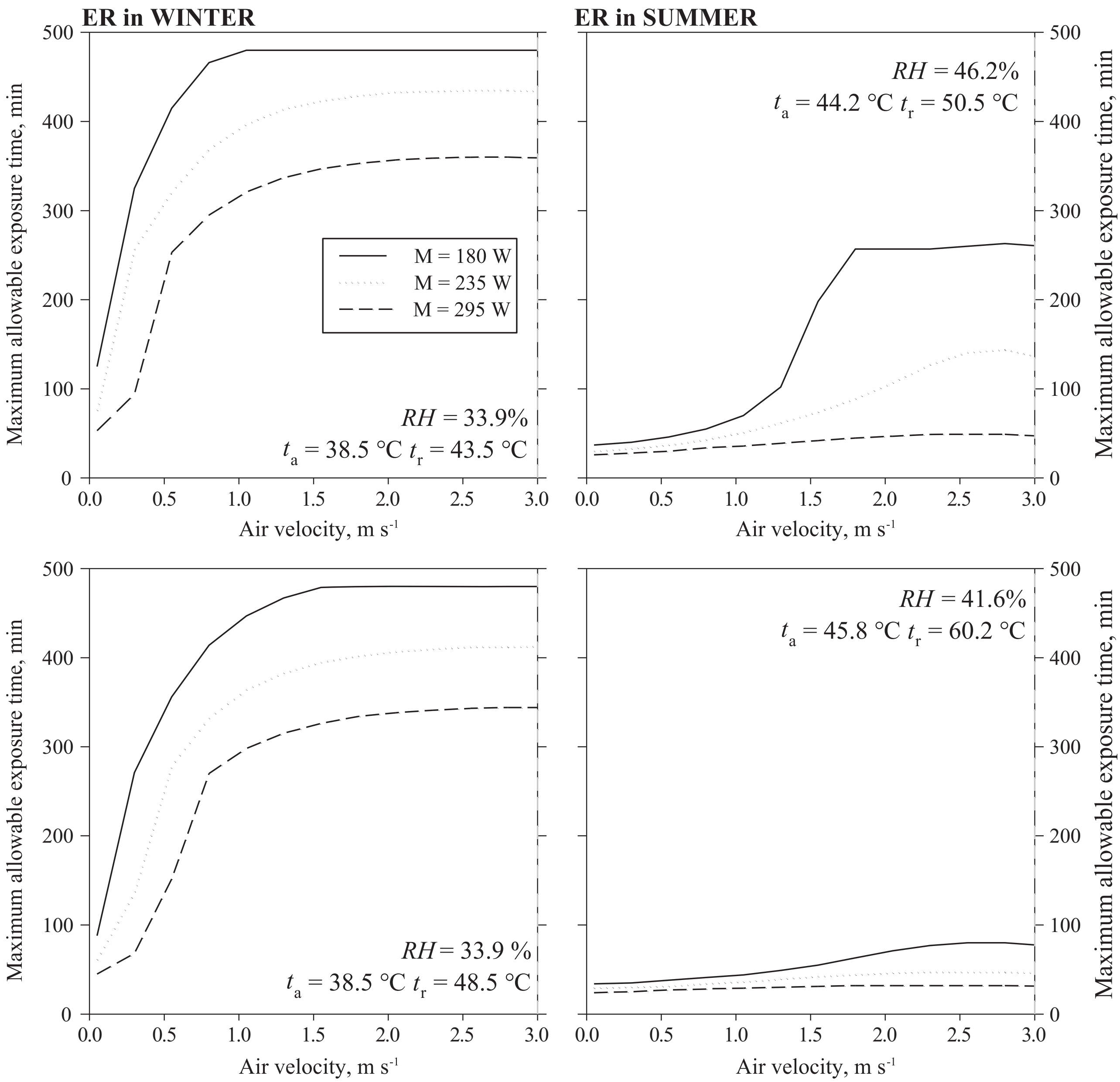

Fig. 2. Effect of the air velocity on the maximum allowable exposure times. In case of winter conditions, mean radiant temperature values were fixed on the basis of literature data (Collins et al., 1971). I_{cl} = 1.0 clo, acclimatized crews.

to 3% of the body mass the maximum water loss (e.g. from 3750 g to 2250 g for a standard subject 75 kg in weight).

- The microclimatic monitoring in ERs is a crucial step in the analysis of working conditions: it is almost absurd that variables such as air velocity and mean radiant temperature, which strongly affect the heat flows between the man and surrounding environment (d'Ambrosio Alfano et al., 2013b), are systematically ignored (Orosa and Oliveira, 2010). From this perspective it is important to observe that in ER it is unlikely to assume uniform conditions (e.g. $t_r = t_a$) as past measurements carried out by Collins et al. (1971) and summarized in Table 2 clearly confirm (t_r values reported in this study are 5–15 °C greater than t_a). To stress the effect of a partial monitoring in terms of mean radiant temperature, in Fig. 1 the effect of t_r on DLEs predicted by PHS is shown. The reduction of DLEs induced by the increase of the mean radiant temperature is pronounced both under still air and in the presence of ventilation and can lead to an underestimation of about 80–100 min (with respect to uniform conditions) in case of $t_r - t_a \leq 10$ °C. On the contrary, a dramatic fall of DLEs is observed if the difference between t_r and t_a exceeds 10 °C, especially at higher metabolic rates (e.g. during emergency repairs) Table 9.

3.3. Case of study 2: oil tanker in summer

Based on data summarized in Table 10, it seems that the combined effect of sea-lane and season strongly affects the indoor microclimatic conditions of the engine room and related service environments such as boiler and pump rooms. Particularly, the highest values of air temperature and mean radiant temperature, due to the combined effect of operating equipment and high external temperatures, result in almost all cases in exposure typical of short term risks (see Table 5), with DLE values half an hour for all levels of metabolic rates (even for M = 180 W which is a typical value for light work on a machine tool).

In all conditions of Table 10, the sweat evaporation does not eliminate all the heat produced inside the body and the core temperature rises sharply above 38 °C. In all cases, the predicted core temperature after 8 h is above 40 °C, indicating a considerable risk of heat stroke or other physiological damage. Moreover, according to DLE values, metabolic activity seems to amplify this phenomenon.

As mentioned for winter conditions, some ventilation improves the situation (see Fig. 2). This is important if the temperature of the ventilated air is not excessive and decreases if it is higher, for being marginal at air temperatures near the skin temperature. Obviously, this is no longer the case when the ventilated air temperature reaches 45 °C and in the presence of high radiative load, the body then receiving heat instead of losing heat from the environment. Under these conditions, evaporation cannot effectively contribute to cooling the body most likely because the sweat rate cannot exceed its maximum value (e.g. 1 kg h^{-1} for not acclimatized people). This is the reason why DLE attempt a plateau value for air velocity values of about 1–2 m s^{-1} depending upon the mean radiant temperature value.

4. Conclusions

Studies devoted to the characterization of working conditions on board ships demonstrated that the engine rooms exhibit the highest stress incidence mainly due to work postures, noise, poor indoor air quality and heat stress. Unfortunately, interest in this topic was mainly focused on the identification of the risk factors to be taken into account at the design and management level rather than on systematic studies devoted to the thermo-hygrometric characterization of such special work environments. Consequently, very little data on microclimatic monitoring is available and no medical surveys in the field on the main indicators of heat strain (e.g, core temperature, water loss) are available. In addition, despite robust and standardized protocols and methods for the assessment of hot working conditions, obsolete or unreliable heat stress indices are still used.

This paper discussed how the ISO 15265 procedure adopting the Screening, Observation, Analysis, Expertize (SOBANE) principles can be easily adopted onboard ships to assess and manage heat stress. The participative character of this strategy can be very effective on board ships because of unique nature of working conditions where cramped living conditions and the natural solidarity among crews promote awareness of the universal importance of safety issues. In this way, crews can play an essential role in the effort to improve on board working conditions.

At analysis level, where highly skilled personnel is required (e.g. occupational health specialists, doctors, ergonomists, and engineers), this paper stressed the need to spend great efforts on the microclimatic monitoring of the most critical areas on board (engine rooms, boiler rooms and similar technical spaces) and to pay attention to the calculation of stress indices. Particularly it has been emphasized that microclimatic monitoring must be carried out by taking into account all four physical variables affecting thermal sensation. In fact, the measurement of only air temperature and humidity leads to wrong assessments of working conditions due to the impossibility of calculating all the required indices and, therefore, of assessing the maximum allowable exposure time. This is very crucial in case of emergency repairs in ER technical areas where metabolic expenditure is measurably higher and the exposure of workers to extreme conditions is conditioned by the duration of repairs (which can exceed the DLEs).

In a future paper, the analysis here discussed will be expanded with a combined subjective, microclimatic and physiological investigation into the thermal stress conditions in several ships (merchant, passenger, and so on) and in different microclimatic conditions (season, routes).

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