

Estimation of respiratory heat flows in prediction of heat strain among Taiwanese steel workers

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Abstract International Organization for Standardization 7933 standard provides evaluation of required sweat rate (RSR) and predicted heat strain (PHS). This study examined and validated the approximations in these models estimating respiratory heat flows (RHF) via convection (C_{res}) and evaporation (E_{res}) for application to Taiwanese foundry workers. The influence of change in RHF approximation to the validity of heat strain prediction in these models was also evaluated. The metabolic energy consumption and physiological quantities of these workers performing at different workloads under elevated wet-bulb globe temperature (30.3 ± 2.5 °C) were measured on-site and used in the calculation of RHF and indices of heat strain. As the results show, the RSR model overestimated the C_{res} for Taiwanese workers by

approximately 3 % and underestimated the E_{res} by 8 %. The C_{res} approximation in the PHS model closely predicted the convective RHF, while the E_{res} approximation over-predicted by 11 %. Linear regressions provided better fit in C_{res} approximation ($R^2 = 0.96$) than in E_{res} approximation ($R^2 \leq 0.85$) in both models. The predicted C_{res} deviated increasingly from the observed value when the WBGT reached 35 °C. The deviations of RHF observed for the workers from those predicted using the RSR or PHS models did not significantly alter the heat loss via the skin, as the RHF were in general of a level less than 5 % of the metabolic heat consumption. Validation of these approximations considering thermo-physiological responses of local workers is necessary for application in scenarios of significant heat exposure.

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Introduction

In Taiwan, 73,847 workers are currently employed by 1279 iron and steel casting factories, representing approximately 3 % of the workforce in the nation's industrial sectors (MOEA 2014). Taiwanese workers engaged in iron and steel casting are frequently working under heavy workload and exposed to significant radiant heat and risk thermal stress. This risk is exacerbated when the workers have to labor in hot seasons and humid climate. Among the manufacturing processes involved in iron and steel casting, the operations in the furnace area subjected the workers to severe thermal stress (Chen et al. 2003).

Heat stress is typically evaluated by monitoring the thermal microclimate in the work environment (Parsons 2013) and interpreted as the wet-bulb globe temperature (WBGT).

However, for evaluating the human thermal perception or thermoregulatory change in response to heat exposure, the WBGT is a less-sufficient measure as it does not take into account the variability in individual susceptibility of the workers to heat stress. The International Organization for Standardization (ISO) Standard 7933 *Ergonomics of the thermal environment—Analytical determination and interpretation of heat stress using calculation of the predicted heat strain* (ISO 7933 2004) and the predicted heat strain (PHS) model described in the standard is among the most frequently applied methods for interpreting the thermal stress imposed on the workers and the thermal strain developed in response.

The PHS model was validated by European research teams (Malchaire et al. 2001, 2002), and the effort was largely associated with validating the prediction of sweat rate and core temperature. In comparison, the approximation of respiratory heat flows (RHF) was less validated using data generated from field studies, particularly for people residing in hot-and-humid areas or for workers engaged in practices involving high temperature. In both cases, the thermal adaptation to local climate or working conditions could result in levels of physical fitness and acclimatization different from those assumed in the PHS model. Havenith and van Middendorp (1990) reported that the heat strain capacity of heat-exposed individuals as manifested in heat storage, body core temperature, and heart rate were influenced by the anthropometric measures (expressed in the surface-to-mass ratio), level of physical fitness (the maximal oxygen uptake), and status of acclimatization (the relationship between sweat rate and rectal temperature). The thermo-physiological responses to heat exposure also vary among different ethnic groups, adding to the complexity of applying the ISO method in different regions of the globe. Fukazawa and Havenith (2012) examined the ethnic differences in thermal response and human thermal comfort sensation between Japanese and Caucasians resting and then walking (4.5 km h^{-1}) under a temperate thermal environment ($t_a = 22 \text{ }^\circ\text{C}$). They observed a significantly higher mean skin temperature and greater rate of water vapor evaporation from the body surface for Japanese than for Caucasians.

The ISO 7933 was first published in 1989 (ISO 7933 1989), and the approximation underlying the thermal stress evaluation in the standard was termed the “required sweat rate (RSR)” model (Youle and Parsons 2009). The revision of the standard in 2004 (ISO 7933 2004) extended the calculation of the RSR index to evaluate the PHS. Both models established calculations to quantitatively describe the different heat transfer processes as defined in the thermal balance equation of the body. In the ISO 7933, the RHF indicating the transfer of metabolic heat and water vapor from the respiratory tract to the inhaled air via convection (C_{res}) and evaporation (E_{res}) are calculated as follows (ISO 7933 2004):

$$C_{\text{res}} = 0.072c_p \times V \times (t_{\text{ex}} - t_a) / A_{\text{Du}} \quad (1)$$

$$E_{\text{res}} = 0.072c_e \times V \times (W_{\text{ex}} - W_a) / A_{\text{Du}} \quad (2)$$

where in Eq. (1), the c_p , V , t_{ex} , t_a , and A_{Du} are the specific heat of dry air at constant pressure ($\text{J kg}^{-1} \text{ dry air Kelvin}^{-1}$), respiratory ventilation rate (L min^{-1}), expired air temperature ($^\circ\text{C}$), air temperature ($^\circ\text{C}$), and DuBois body surface area (m^2), respectively; in Eq. (2) the c_e , V , W_{ex} , W_a , and A_{Du} are the water latent heat of vaporization (J kg^{-1}), respiratory ventilation rate (L min^{-1}), humidity ratio for the expired air ($\text{kg water kg}^{-1} \text{ dry air}$), humidity ratio of the inhaled air ($\text{kg water kg}^{-1} \text{ dry air}$), and DuBois body surface area (m^2). Both the C_{res} and E_{res} share a unit of watts per square meters (W m^{-2}).

When the metabolic rate (M ; W m^{-2}) can be determined, a relation $V / A_{\text{Du}} = kV \times M$ (with kV being a constant) may be empirically derived and substituted into Eqs. (1) and (2) to obtain equations that allow for the use of M as a parameter in the calculation of C_{res} and E_{res} . In the RSR model as adopted in the 1989 version of ISO 7933, these calculations are as follows:

$$C_{\text{res(RSR)}} = 0.0014 \times M \times (t_{\text{ex}} - t_a) \quad (3)$$

$$E_{\text{res(RSR)}} = 0.0173 \times M \times (p_{\text{ex}} - p_a) \quad (4)$$

where in Eq. (4), the p_{ex} and p_a are the saturated water vapor pressure in the expired air (kPa) and the partial water vapor pressure in the inhaled air (kPa), respectively. The t_{ex} varies with the temperature and the humidity of the inhaled air. As the RHF by convection is small compared to those generated by other heat transfer processes, the ISO 7933 RSR model recommended in the hot environment to adopt a constant value of $35 \text{ }^\circ\text{C}$ (ISO 7933 1989) for the t_{ex} . Likewise, for the p_{ex} in Eq. (4), a value of 5.624 kPa was recommended when the default t_{ex} of $35 \text{ }^\circ\text{C}$ was used. Although Eqs. (3) and (4) were phased out in the 2004 revision of ISO 7933, they are still adopted in the current ISO 7730 (2005) and being widely used in the calculation of the predicted mean vote for interpreting thermal comfort.

In the 2004 revision of ISO 7933, the C_{res} and E_{res} in the PHS model are approximated following (Malchaire et al. 2002, 2001):

$$C_{\text{res(PHS)}} = 0.00152 \times M \times (28.6 + 0.641p_a - 0.885t_a) \quad (5)$$

$$E_{\text{res(PHS)}} = 0.00127 \times M \times (59.3 + 0.53t_a - 11.63p_a) \quad (6)$$

The parameters in Eqs. (5) and (6) share the same definitions as those in Eqs. (3) and (4). The empirical equation adopted in the PHS model for calculating $C_{\text{res(PHS)}}$ was obtained by substituting the relationships that Livingstone et al. (1994) reported between the M , V , t_{ex} , t_a , and p_a into Eq. (1). Specifically, a relationship of 0.076 W for production of metabolic heat per unit of ventilation rate (L min^{-1}) and the

expression $t_{ex} (^\circ\text{C}) = 28.6 + 0.115 t_a (^\circ\text{C}) + 0.641 p_a (\text{kPa})$ were substituted into Eq. (1) to obtain Eq. (5) for calculating the sensible respiratory heat loss. For Eq. (6), the E_{res} was adopted as proposed by Varene (1986).

Study goals

This study evaluated the thermo-physiological changes of furnace area workers in Taiwanese foundries in response to high temperature and radiant heat. In the study, physiological measurements were applied to assess the validity of the RHF approximations as outlined in the RSR and PHS models when applied to the foundry workers. The approximations in the models were subsequently validated by means of linear regression for domestic application. In addition, the validity of the RSR and PHS models evaluating the heat strain manifested as the evaporative heat flow on the skin, skin wettedness, and sweat rate was also analyzed to investigate the influence of RHF approximations to heat strain evaluation when these approximations were first validated using local workers' physiological measurements.

Materials and methods

Study design

A field study was conducted in Taiwanese foundries to evaluate the exposure of furnace area workers to radiant heat. The on-site evaluation consisted of environmental monitoring and thermo-physiological measurement. The measurements taken for thermo-physiological responses were used to determine the parameters required as input in the calculation of RHF. The results of calculation were used to evaluate the validity of $C_{res(RSR)}/E_{res(RSR)}$ and $C_{res(PHS)}/E_{res(PHS)}$ approximations and then to validate these approximations. To evaluate how the deviation in magnitude of the RHF observed for the workers from those predicted using the RSR and PHS models might influence the assessment of heat strain, the indices of heat strain common in both models for interpreting the thermo-physiological responses required to maintain heat balance and the responses considered physiologically achievable were also analyzed and compared.

In this evaluation, the RHF via convection and evaporation for Taiwanese workers ($C_{res(TW)}$ and $E_{res(TW)}$, respectively) were first determined following Eqs. (1) and (2) of the ISO 7933 using values of climatic variables monitored and those of physiological measurements taken on-site when the workers performed near the furnace. The $C_{res(TW)}$ and $E_{res(TW)}$ represented the RHF values observed for Taiwanese foundry workers. To examine the validity of the RHF approximations in the RSR and PHS models for application to Taiwanese workers, the C_{res} and E_{res} were also predicted using

the approximations in the RSR model ($C_{res(RSR)}$ and $E_{res(RSR)}$) as presented in Eqs. (3) and (4), respectively, and using those in the PHS model ($C_{res(PHS)}$ and $E_{res(PHS)}$) as presented in Eqs. (5) and (6). The $C_{res(RSR)}$ and $C_{res(PHS)}$ were compared to the $C_{res(TW)}$ and the $E_{res(RSR)}$ and $E_{res(PHS)}$ compared to the $E_{res(TW)}$ to identify the statistical significance of any differences between the predicted and the observed values. In these calculations, the default values of 35 °C and 5.624 kPa as suggested in Eqs. (3) and (4) were used for t_{ex} and p_{ex} , respectively. If a statistically significant difference was found, linear regression of $C_{res(TW)}$ against $C_{res(RSR)}$ or $C_{res(PHS)}$ and of $E_{res(TW)}$ against $E_{res(RSR)}$ or $E_{res(PHS)}$ was performed to quantitatively describe the relationship between the RHF observed for Taiwanese workers and their counterparts predicted using the models.

Two sets of indices shared in both the RSR and PHS models for interpreting the heat strain were calculated: the required evaporative heat flow (E_{req} ; termed the required evaporation rate in the RSR model), the required skin wettedness (w_{req}), and the required sweat rate (Sw_{req}) as well as the predicted evaporative heat flow (E_p ; termed the predicted evaporation rate in the RSR model), the predicted skin wettedness (w_p), and the predicted sweat rate (Sw_p). The E_{req} , E_p , Sw_{req} , and Sw_p have a unit of watts per square meter; the w_{req} and w_p are dimensionless. In the analysis, the $C_{res(TW)}/E_{res(TW)}$ were applied in both models to calculate these indices, and the calculated indices were compared to those generated using the $C_{res(RSR)}/E_{res(RSR)}$ or the $C_{res(PHS)}/E_{res(PHS)}$. When a statistically significant difference was found, the discrepancy in magnitude in relation to the RHF was quantitatively described to reveal the influence that the RHF approximations might have to the heat strain evaluation when these approximations were first validated using local workers' observations.

Study sites and participants

The on-site monitoring was conducted in the furnace areas of two iron smelting and steel casting facilities in Tainan (hereafter renamed as foundry A and foundry B) located in south Taiwan. Both facilities were three-floor buildings. The first floor included areas of maintenance and storage of stock materials (iron ores); the second and the third floors were where the iron smelting and steel casting took place, respectively. In this study, the environmental monitoring and physiological measurement were conducted on the second floor at a distance of approximately 20 m from the electrical arc furnaces to minimize the interruption of field study to the ironwork. A total of 30 male workers from foundry A and 67 males from foundry B volunteered to participant. These workers were of an age between 20 and 40 years, and they had been engaged in the casting work for at least 3 years and were heat

acclimatized. Table 1 shows the distribution of their anthropometric data.

On-site field study

In the field study, the workers were required to exercise on a WESLO/Spectra Scan treadmill of controlled slope and speed (ICON Health & Fitness, Logan, UT, USA) near the furnaces to develop different levels of metabolic energy consumption. Individual sessions of the study took place at the foundries from late afternoon to late evening, beginning approximately after 5 pm. The precise duration of each session depended on the hours of the task on-site as prompted by the production demand. The Taiwanese regulations required (MOL 1998) that the WBGT in the furnace area was to be maintained between 26 and 33 °C during the working period, and under this temperature, the workers were expected to conduct their task (i.e., tapping melted metal or slag) and rest following a schedule of 67 % time for work and 33 % for rest within a single work cycle. In this study, the thermal environment was monitored on-site. The temperature by which the experiment to begin was determined at the beginning of each session when the task schedule was available from the foundry management. When the task on the day required extended operation of the furnace, a higher temperature was targeted. The waiting period was at least 30 min.

Each individual session began with setting up the equipments for monitoring the thermal climate. Simultaneously, the workers were surveyed for their anthropometric data and briefed for the study procedure. They were also measured for readings of heart rate, blood pressure, and clothing weight.

Table 1 Anthropometrics of study participants and distribution of climatic variables in studied iron and steel casting plants (foundries A and B)

	Foundry A	Foundry B	All
Anthropometrics of participants			
Number (<i>n</i>)	30	67	97
Age (years)	31.9 ± 4.9	26.4 ± 5.1	28.0 ± 5.6
Height (cm)	164.7 ± 8.2	170.8 ± 4.2	169.0 ± 6.3
Weight (kg)	64.9 ± 14.6	71.0 ± 9.3	69.2 ± 11.4
BMI (kg m ⁻²)	23.9 ± 3.0	24.3 ± 3.2	24.2 ± 3.1
Distribution of climatic variables			
<i>t_w</i> (°C)	26.0 ± 2.1	27.9 ± 1.7	27.3 ± 20.3
<i>t_a</i> (°C)	34.1 ± 4.9	34.5 ± 4.4	34.4 ± 4.5
<i>t_g</i> (°C)	35.3 ± 4.4	38.1 ± 4.3	37.3 ± 4.5
WBGT (°C)	28.8 ± 2.7	31.0 ± 2.1	30.3 ± 2.5
<i>v_a</i> (m s ⁻¹)	0.8 ± 0.8	0.6 ± 0.3	0.6 ± 0.5

Values are mean ± SD

t_w web-bulb temperature, *t_a* dry-bulb temperature, *t_g* globe temperature, WBGT wet-bulb globe temperature, *v_a* air speed

Afterwards, the participants carrying equipments of physiological measurement exercised on the treadmill at the designated speed and practiced mouth-breathing. Once the environmental temperature reached the target level, the experiment began and the physiological measurement took place. In each session, the exercise continued for a period of 15 min. The treadmill was set at a slope of 10 % and run at a speed of 0.54, 1.07, or 1.34 m s⁻¹ to create a metabolic rate of 114.3 ± 9.7, 200.6 ± 29.1, or 268.0 ± 14.9 W m⁻². The selected levels of metabolic rates corresponded to the three categories of workload legally recognized by Taiwan's occupational safety and health authority (MOL 1998) as light work (<133.1 W m⁻²), moderate work (133.1–232.6 W m⁻²), and heavy work (>232.6 W m⁻²). All participants had similar clothing at work and during the test, including a cotton brief, t-shirt, fitted cotton overall, socks, and heavy work shoes (0.55–0.61 clo).

Environmental monitoring

The thermal climate on-site was monitored for the air temperature (*t_a*), wet-bulb temperature (*t_w*), globe temperature (*t_g*), air velocity (*v_a*), relative humidity (*rh*), and WBGT. The *t_a*, *t_g*, and the corresponding WBGT were monitored using a thermal environment monitor (QT-15, Quest Technologies, Oconomowoc, WI, USA), and the *t_w* and *rh* were determined using an Assman and Sling psychrometer (TES-1361, TES, Taipei, Taiwan). The readings of *t_w*, *t_a*, and *t_g* were taken immediately before and after each study session; those of *t_a* were also taken by the minute during the physiological measurement. The *v_a* was measured 1 min before and after the physiological measurement using a hot-wired anemometer (AVM-07, TES, Taipei, Taiwan). The mean radiant temperature (*t_r*) and *p_a* were calculated as prescribed in the ISO 7726 (1998).

Physiological monitoring

In the study, the *M* of each worker was determined from the oxygen consumption rate following the method prescribed in the ISO 8996 (2004). As introduced in the section “On-site field study,” the workers were required to exercise on a treadmill to develop the metabolic energy consumption simulating different levels of workload. During the exercise, the air exhaled by the worker was directed via a unidirectional check valve into a mix chamber where the O₂ and CO₂ concentrations were measured using an O₂ analyzer (precision ±0.01 %) calibrated by 16 % O₂ (Ametek Oxygen Analyzer S-3A, VacuMed, Ventura, CA, USA) and a CO₂ analyzer (precision ±0.01 %) calibrated by 5 % CO₂ (Medical Gas Analyzer LB, SensorMedics, Milano, Italy) for determining the percentages of O₂ and CO₂ in the exhaled air. The air flow was directed to pass through a dry-air gas analyzer for determination of the exhaled air volume. The readings were taken at an interval of

1 min and converted to the percentages of O₂ and CO₂ and the volume of respiratory ventilation. The aural temperature was taken at an interval of 1 min using a thermometer (precision ±0.1 °C) (QUESTEMP[®]II Personal Heat Stress Monitor, 3M Personal Safety Division, Oconomowoc, WI, USA) to indicate the core body temperature. The heart rate (HR) was measured every 15 s using a real-time HR monitor (Polar Accurex Plus Heart Rate Monitor, Polar Electro Oy, Kempele, Finland) following the procedure outlined in the ISO 9886 (2004).

Results

Status of thermal environment vs. range of validity in RSR and PHS models

As Table 1 shows, the furnace areas of the two foundries shared a similar thermal climate, although the radiant heat was more significant in foundry B—the mean *t_g* in foundry B was 2.8 °C higher than in foundry A (*t* test, *P* < 0.01), resulting in a greater level of heat stress as manifested in the WBGT (*P* < 0.01). Compared to the ranges of validity indicated in the ISO 7933 (Table 2), both the upper boundaries of the *t_a* and *t_r* in the foundries were higher than the upper levels of application suggested for the RSR model. The mean value of observed *t_r* was 3.7 °C greater than the level reported in the range of validity for the RSR model (*P* < 0.01). The mean of observed *p_a* was also greater than the level recommended for application of the RSR model (*P* < 0.01). For the PHS model,

Table 2 Range of climatic variables observed in studied iron and steel casting plants (foundries A and B) in comparison with range of validity for application of required sweat rate (RSR) and predicted heat strain (PHS) models specified respectively in ISO 7933:1989 (ISO 7933 1989) and ISO 7933:2004 (ISO 7933 2004)

	Studied sites (foundries A and B)	RSR Model ^a (ISO 7933:1989)	PHS Model (ISO 7933:2004)
<i>t_a</i> (°C)	25.4–57.6 (34.4 ± 4.5)	22.9–50.6 (35.2 ± 7.7)	15–50
<i>t_r</i> (°C)	28.7–59.1 (38.3 ± 5.31)	24.1–49.5 (34.6 ± 6.5)	
<i>t_r</i> – <i>t_a</i> (°C)	0.2–17.0		0–60
<i>v_a</i> (m s ⁻¹)	0.1–2.6 (0.6 ± 0.5)	0.2–0.9 (0.3 ± 0.2)	0–3
<i>p_a</i> (kPa)	2.5–4.2 (3.1 ± 0.5)	0.8–4.8 (2.2 ± 1.1)	0–4.5

Values reported are ranges of each variable and those in parentheses are mean ± SD

t_a dry-bulb temperature, *t_r* mean radiant temperature, *t_r*–*t_a* difference between *t_r* and *t_a*, *v_a* air speed, *p_a* water vapor partial pressure

^a Range of validity indicated for RSR model was specified in Table C.1 of ISO 7933:1989 in accordance with data used in determination of mean skin temperature in RSR model development

the distribution of all climatic variables was within the range of validity except for *t_a*—the upper bound of observed *t_a* exceeded the range of *t_a* recommended for the application of the PHS model. The difference between *t_r* and *t_a* as monitored on-site was approaching the lower bound of the validity range possibly due to the significant *t_a* in these foundries. These results suggested that the thermal environment in these facilities was likely hotter than those assumed in both the RSR and PHS models.

Evaluation and validation of respiratory heat flow approximations: RSR model

The comparison of the *C_{res(TW)}* and *E_{res(TW)}* with the *C_{res(RSR)}* and *E_{res(RSR)}*, respectively, by means of the paired *t* test indicated a statistically significant difference between these two sets of values for both the *C_{res}* and *E_{res}* (*P* < 0.0001; *n* = 971). The regression of the *C_{res(TW)}* and *E_{res(TW)}* against the *C_{res(RSR)}* and *E_{res(RSR)}*, respectively, yielded domestically applicable approximations (Fig. 1):

$$C_{res(TW)} = 0.972 \times C_{res(RSR)} - 0.047 \quad (R^2 = 0.96) \quad (7)$$

$$E_{res(TW)} = 1.074 \times E_{res(RSR)} + 0.065 \quad (R^2 = 0.85) \quad (8)$$

In Eq. (7), the slope was of a value less than one and the intercept of a negative value, suggesting an overestimation of the RHF via convection for Taiwanese workers by the *C_{res(RSR)}*. In comparison, the RHF via evaporation for Taiwanese workers appeared to be greater than the *E_{res(RSR)}* predicted in the RSR model (Eq. (8)). These results suggested that for these foundry workers, a greater respiratory evaporative heat flow was produced than the level the RSR model predicted. This inference was supported by the ratio of *C_{res(TW)}* to *C_{res(RSR)}* and of *E_{res(TW)}* to *E_{res(RSR)}* when they were calculated assuming a linear, constant relationship:

$$C_{res(TW)} = 0.971 \times C_{res(RSR)} \quad (R^2 = 0.96) \quad (9)$$

$$E_{res(TW)} = 1.080 \times E_{res(RSR)} \quad (R^2 = 0.85) \quad (10)$$

Overall, the *C_{res(TW)}* was approximately 3 % less than the *C_{res(RSR)}* and the *E_{res(TW)}* 8 % more than the *E_{res(RSR)}*. Greater residuals in the regression were observed in the areas of low *C_{res}* and high *E_{res}*, suggesting a lesser applicability of these RHF approximations in situations where the weight of respiratory evaporation as a mechanism of metabolic heat dissipation increased and became predominant. This situation would occur when the workers performed strenuously in a very warm or hot environment. As shown in Fig. 2a, the residual between the *C_{res(TW)}* and *C_{res(RSR)}* became significant when the WBGT monitored on-site exceeded approximately 35 °C. However, the change in residual between the *E_{res(TW)}* and *E_{res(RSR)}* was less prominent (Fig. 2b).

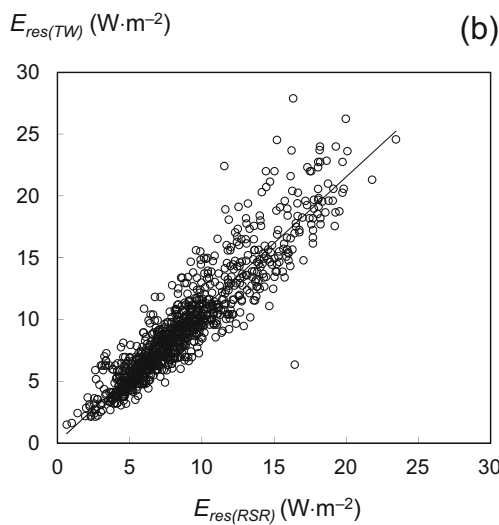
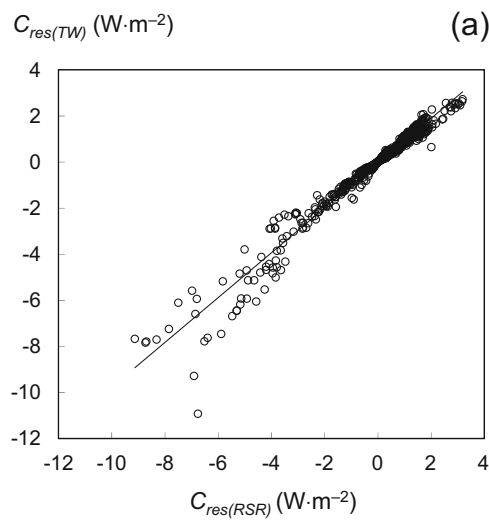


Fig. 1 Regression of **a** $C_{res(TW)}$ against $C_{res(RSR)}$ and **b** $E_{res(TW)}$ against $E_{res(RSR)}$ for validation of $C_{res(RSR)}$ and $E_{res(RSR)}$ approximations in required sweat rate (RSR) model for application to Taiwanese foundry workers. Regression models and coefficients of determination corresponding to *solid lines* in **(a)** and **(b)** are presented in Eqs. (7) and (8), respectively. $C_{res(TW)}$ respiratory convective heat flow observed for Taiwanese workers, $C_{res(RSR)}$ respiratory convective heat flow predicted using approximation in RSR model, $E_{res(TW)}$ respiratory evaporative heat flow observed for Taiwanese workers, $E_{res(RSR)}$ respiratory evaporative heat flow predicted using approximation in RSR model

Evaluation and validation of respiratory heat flow approximations: PHS model

The paired *t* test between the $C_{res(TW)}$ and $E_{res(TW)}$ and the $C_{res(PHS)}$ and $E_{res(PHS)}$, respectively, revealed a statistically significant difference between these two datasets for both the C_{res} and E_{res} ($P < 0.0001$; $n = 971$). The regression of the $C_{res(TW)}$ and $E_{res(TW)}$ against the $C_{res(PHS)}$ and $E_{res(PHS)}$, respectively, yielded domestically applicable approximations (Fig. 3):

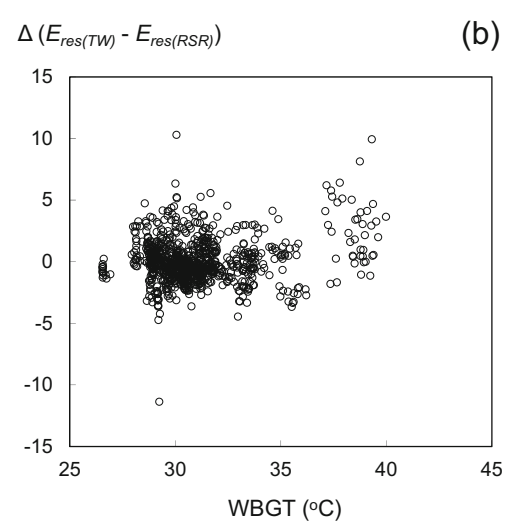
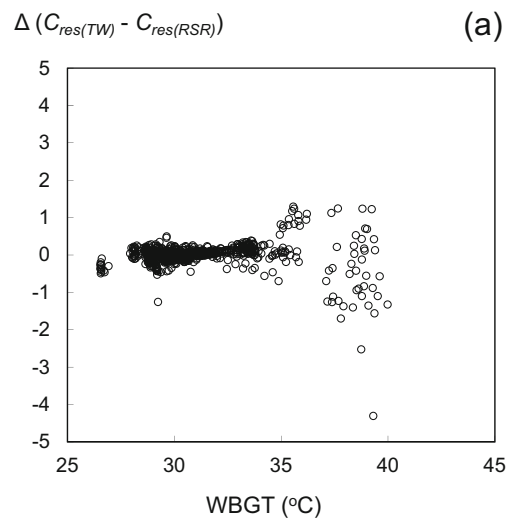


Fig. 2 Distribution of **a** $\Delta(C_{res(TW)} - C_{res(RSR)})$ and **b** $\Delta(E_{res(TW)} - E_{res(RSR)})$ against WBGT. Δ residual between observed and predicted heat flow, $C_{res(TW)}$ respiratory convective heat flow observed for Taiwanese workers, $C_{res(RSR)}$ respiratory convective heat flow predicted using approximation in required sweat rate (RSR) model, $E_{res(TW)}$ respiratory evaporative heat flow observed for Taiwanese workers, $E_{res(RSR)}$ respiratory evaporative heat flow predicted using approximation in RSR model, WBGT wet-bulb globe temperature

$$C_{res(TW)} = 1.001 \times C_{res(PHS)} + 0.062 \quad (R^2 = 0.96) \quad (11)$$

$$E_{res(TW)} = 0.900 \times E_{res(PHS)} - 0.156 \quad (R^2 = 0.82) \quad (12)$$

As Eq. (11) shows, the $C_{res(PHS)}$ approximation was able to closely predict the RHF via convection for Taiwanese workers. The small intercept in Eq. (11) suggested a greater production of baseline respiratory convective heat for these foundry workers than the level the $C_{res(PHS)}$ predicted. In comparison, the RHF via evaporation for Taiwanese workers appeared to be less than the level the $E_{res(PHS)}$ predicted in the PHS model (Eq. (12)). The analysis of the ratio of $C_{res(TW)}$ to $C_{res(PHS)}$ and of $E_{res(TW)}$ to $E_{res(PHS)}$ revealed the following:

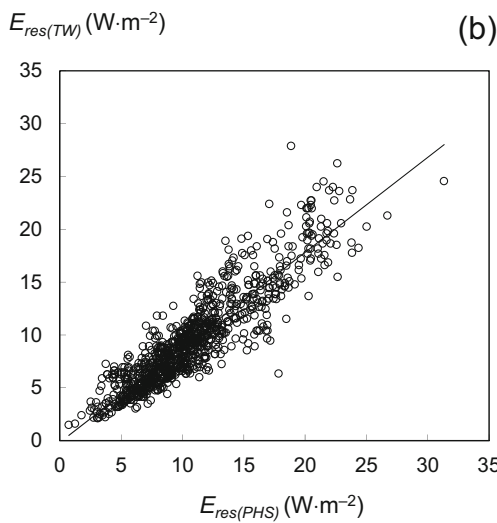
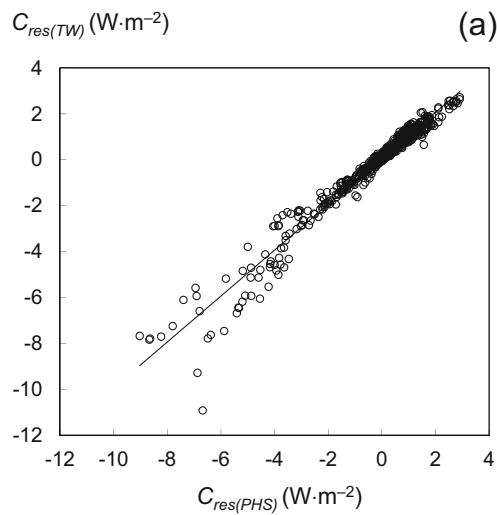


Fig. 3 Regression of **a** $C_{res(TW)}$ against $C_{res(PHS)}$ and **b** $E_{res(TW)}$ against $E_{res(PHS)}$ for validation of $C_{res(PHS)}$ and $E_{res(PHS)}$ approximations in predicted heat strain (PHS) model for application to Taiwanese foundry workers. Regression models and coefficients of determination corresponding to *solid lines* in **(a)** and **(b)** are presented in Eqs. (11) and (12), respectively. $C_{res(TW)}$ respiratory convective heat flow observed for Taiwanese workers, $C_{res(PHS)}$ respiratory convective heat flow predicted using approximation in PHS model, $E_{res(TW)}$ respiratory evaporative heat flow observed for Taiwanese workers, $E_{res(PHS)}$ respiratory evaporative heat flow predicted using approximation in PHS model

$$C_{res(TW)} = 1.000 \times C_{res(PHS)} \quad (R^2 = 0.96) \quad (13)$$

$$E_{res(TW)} = 0.887 \times E_{res(PHS)} \quad (R^2 = 0.82) \quad (14)$$

As Eqs. (13) and (14) show, the $C_{res(TW)}$ was approximately the same level the $C_{res(PHS)}$ predicted and the $E_{res(TW)}$ was 11 % less than the predicted value. Similar to the distribution observed for the $C_{res(TW)}$ against $C_{res(RSR)}$ and for the $E_{res(TW)}$ against $E_{res(RSR)}$, greater residuals in the regression for Eqs. (11) and (12) appeared in the areas of low C_{res} and high E_{res} . As Fig. 4 shows, the residual between the $C_{res(TW)}$ and

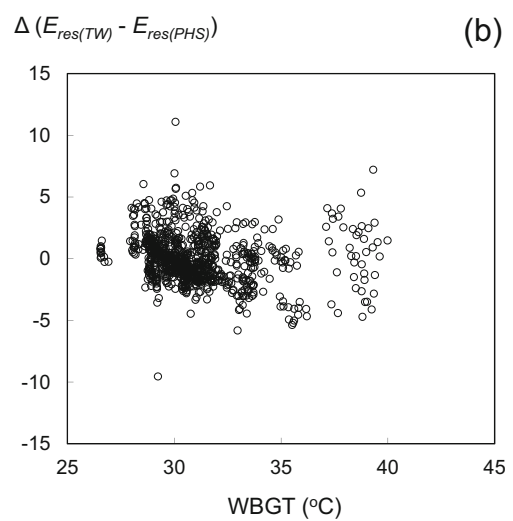
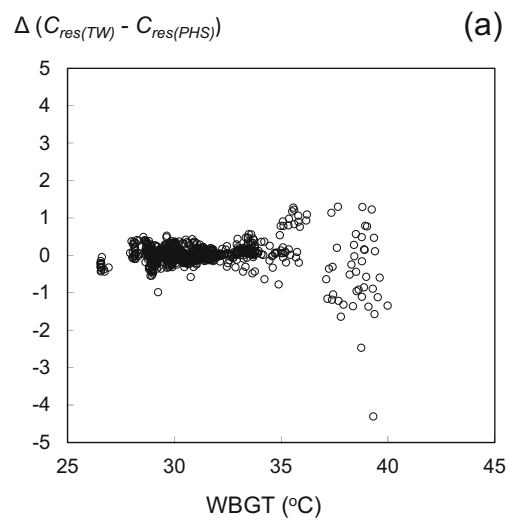


Fig. 4 Distribution of **a** $\Delta(C_{res(TW)} - C_{res(PHS)})$ and **b** $\Delta(E_{res(TW)} - E_{res(PHS)})$ against WBGT. Δ residual between observed and predicted heat flow, $C_{res(TW)}$ respiratory convective heat flow observed for Taiwanese workers, $C_{res(PHS)}$ respiratory convective heat flow predicted using approximation in predicted heat strain (PHS) model, $E_{res(TW)}$ respiratory evaporative heat flow observed for Taiwanese workers, $E_{res(PHS)}$ respiratory evaporative heat flow predicted using approximation in PHS model, WBGT wet-bulb globe temperature

$C_{res(PHS)}$ once again became significant when the WBGT reached 35 °C.

Respiratory ventilation and metabolic rates of foundry workers and application in respiratory heat flow approximation

As introduced, when empirical values of V , A_{Du} , and M are available, the relationship $V / A_{Du} = kV \times M$ may be empirically derived and substituted into Eqs. (1) and (2) to obtain equations resembling the C_{res} and E_{res} approximations as presented in the RSR model ($C_{res(RSR)}$ and $E_{res(RSR)}$). In this study, the V of Taiwanese foundry workers increased

proportionally with increasing M (Fig. 5), and a relationship $V/A_{Du} = (0.073 \pm 0.019) M$ was derived. The kV of 0.073 as identified for Taiwanese workers was of a level comparable to the kV applied in the RHF approximation of the RSR model, 0.070, considering the significant coefficient of variation (>26 %) of the kV identified for Taiwanese workers.

Substituting this relationship and a c_p of $0.02 \text{ W min L}^{-1} \text{ }^\circ\text{C}^{-1}$ into Eq. (1), the following C_{res} approximation was obtained:

$$C_{res(\text{RSR-Adj})} = 0.00146 \times M \times (t_{ex} - t_a) \quad (15)$$

Similarly, substituting into Eq. (2) the relationship $V/A_{Du} = 0.073 M$, a c_e of $42.8 \text{ W min L}^{-1}$, $W_{ex} = 0.0065 \times p_{ex}$, and $W_a = 0.0065 \times p_a$, the following E_{res} approximation was obtained:

$$E_{res(\text{RSR-Adj})} = 0.02031 \times M \times (p_{ex} - p_a) \quad (16)$$

The $C_{res(\text{RSR-Adj})}$ and $E_{res(\text{RSR-Adj})}$ represented the $C_{res(\text{RSR})}$ and $E_{res(\text{RSR})}$ approximations adjusted for Taiwanese workers using the local workers' V , A_{Du} , and M data. However, while the $C_{res(\text{RSR-Adj})}$ was well correlated to the $C_{res(\text{TW})}$ ($R = 0.98$), these two sets of values were statistically different (paired t test, $P < 0.0001$). Similarly, the $E_{res(\text{RSR-Adj})}$ was significantly correlated to but different from the $E_{res(\text{TW})}$ ($R = 0.92$; $P < 0.0001$).

Influence of respiratory heat flow approximation to heat strain evaluation

Table 3 summarizes the heat strain indices estimated by the RSR and PHS models before and after the validation of the models' RHF approximations using the $C_{res(\text{TW})}$ and $E_{res(\text{TW})}$

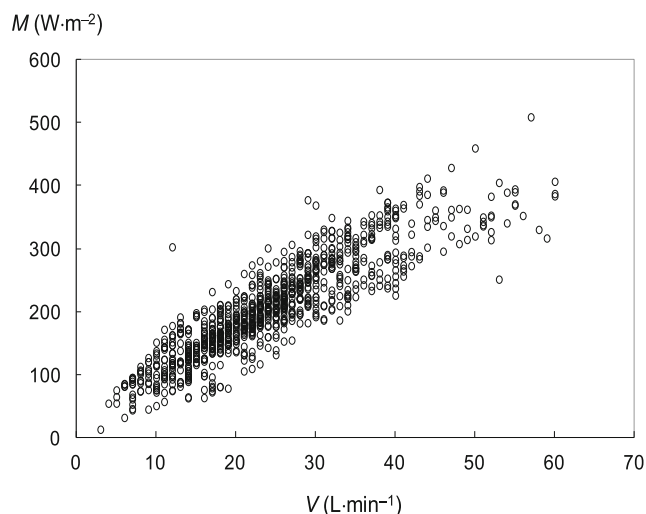


Fig. 5 Distribution of M against V among Taiwanese foundry workers as measured in iron and steel plants. M metabolic rate, V respiratory ventilation rate

observed for Taiwanese foundry workers. All differences identified in the comparison were statistically significant at a level of $P < 0.001$.

In the case of the RSR model, the release of metabolic heat as RHF (i.e., C_{res} and E_{res}) increased slightly after the validation, with the difference being approximately 9.3 % of the RHF estimated using the RSR model before validation. This increase in RHF was associated with a reduction in the E_{req} , and Sw_{req} . However, the reduction in the required heat loss on the skin was only minor—the E_{req} estimated by the validated model was approximately 3.3 % less than the level predicted by the RSR model before validation of RHF approximations, and the Sw_{req} was 6.7 % less. As the RHF were only a small fraction (4.3–4.7 %) of the released metabolic heat, its increase due to the validation of RHF approximations using local workers' physiological data was sufficiently balanced with a reduction to a lesser extent in the requirement of evaporation and sweating on the skin. The reduction in the predicted dermal heat loss was even lower than the level observed for the required loss—the decrease in the E_p and Sw_p in response to the increase of RHF for the foundry workers were less than 0.3 %. In comparison, the validation of RHF approximations in the PHS model resulted in a decrease by 13.5 % of the RHF for the workers. Nonetheless, this decrease did not appear to impact on the estimation of E_{req} and Sw_{req} as much as it did in the RSR model: the E_{req} estimated by the PHS model after validation was increased by only 0.7 % and the Sw_{req} by 0.5 %. The E_p estimated by the validated model was increased by 0.4 % and the Sw_p by 0.7 %.

Discussion

The ISO 7933 standard provides a physiologically sound tool for heat strain evaluation; however, the validity of the RHF approximations in its evaluation has not received sufficient attention when compared to that for the modeling of heat flows via the skin. Malchaire et al. (2001, 2002) in their validation of the PHS model indicated that the loss of metabolic heat through respiratory heat exchange was quite limited in hot climates but still could be of the same order of magnitude as the convective heat loss on the body surface.

In this study, the thermo-physiological responses of Taiwanese foundry workers were measured and applied in validating the C_{res} and E_{res} approximations in the RSR and PHS models and in evaluating the influence of RHF approximations to the development of heat flows on the skin. The hot-and-humid and nearly windless attributes of the investigated foundries and the close proximity of the workers to the furnace distinguished the thermal climate that the workers encountered from those typically assumed in the RSR and PHS models. The RHF approximations in the RSR model overestimated the C_{res} for Taiwanese workers by

Table 3 Respiratory heat flows (RHF) and indices of heat strain estimated by the required sweat rate (RSR) and predicted heat strain (PHS) models before and after validation of RHF approximations in the models using physiological measurements for Taiwanese workers engaged in iron and steel casting

	RSR Model (ISO 7933 1989)		PHS Model (ISO 7933 2004)	
	Before validation	After validation*	Before validation	After validation*
C_{res} ($W m^{-2}$)	0.115 ± 0.068	0.068 ± 0.068	0.002 ± 0.060	0.064 ± 0.059
E_{res} ($W m^{-2}$)	8.806 ± 1.059	9.532 ± 1.138	10.734 ± 1.278	9.141 ± 1.107
$C_{res} + E_{res}$ ($W m^{-2}$)	8.921 ± 1.094	9.601 ± 1.174	10.736 ± 1.298	9.205 ± 1.127
$(C_{res} + E_{res}) / M$	0.043 ± 0.000	0.047 ± 0.000	0.052 ± 0.000	0.045 ± 0.000
E_{req} ($W m^{-2}$)	199.626 ± 20.925	198.975 ± 20.854	212.118 ± 22.318	213.585 ± 22.474
w_{req}	1.204 ± 0.117	1.200 ± 0.117	1.045 ± 0.086	1.051 ± 0.086
Sw_{req} ($W m^{-2}$)	221.596 ± 68.553	206.697 ± 68.374	323.232 ± 35.844	324.723 ± 35.926
E_p ($W m^{-2}$)	156.741 ± 12.559	156.497 ± 12.565	178.827 ± 15.869	179.534 ± 15.897
w_p	0.873 ± 0.054	0.871 ± 0.054	0.825 ± 0.048	0.827 ± 0.047
Sw_p ($W m^{-2}$)	280.402 ± 29.868	279.669 ± 29.818	345.564 ± 96.746	347.957 ± 95.664

Values are mean ± SD

C_{res} respiratory convective heat flow, E_{res} respiratory evaporative heat flow, M metabolic rate, E_{req} required evaporation rate (RSR model) or required evaporative heat flow (PHS model), w_{req} required skin wettedness, Sw_{req} required sweat rate, E_p predicted evaporation rate (RSR model) or predicted evaporative heat flow (PHS model), w_p predicted skin wettedness, Sw_p predicted sweat rate

^a M ($W m^{-2}$) was determined from the oxygen consumption rate of the worker exercising at a speed of 0.54, 1.07, or 1.34 $m s^{-1}$ on a treadmill set at a slope of 10 % for 15 min following the method prescribed in the ISO 8996 (2004). All workers had similar clothing at an insulation level of 0.55–0.61 clo

*Values generated by the models before and after validation were compared using the paired t test; all differences were statistically significant at a level of $P < 0.001$

approximately 3 % and underestimated the E_{res} by 8 %. The C_{res} approximation in the PHS model was able to closely predict the convective RHF for these workers, while the E_{res} approximation over-predicted the evaporative RHF by 11 %. Once validated, these approximations provided reasonable estimates for the local workers.

In either of the RSR and PHS models, the prediction of RHF was less effective when the C_{res} approached the low end and the E_{res} the high end, which occurred when the environmental conditions became hot and the workload required a significant metabolic heat production. In both models, the significant deviation of the predicted C_{res} from the observed value occurred when the WBGT exceeded approximately 35 °C, whereas a similarly significant deviation was not identified in the E_{res} prediction. These results indicated that in the environment where these workers performed their tasks the temperature was a significant factor influencing the prediction of respiratory convective heat flow. Physiologically, heat-acclimatized individuals exhibited increased sweating efficiency, greater sweat secretion, and a stabilized circulation. Also observed would include a lower rate of rise in the heart rate and core temperature as well as an increase in the cardiac output. Figure 6 shows the HR as well as the ratios of M to HR and to V for Taiwanese workers during the period of physiological monitoring. As the data show, these workers appeared to adapt to the workload and the thermal environment swiftly once the exercise began, as the HR as well as the ratio of M to

V and of M to HR stabilized in the first 4 min of the exercise, suggesting a consistent production of metabolic heat. Acclimatization among these foundry workers could have resulted in a state of heat strain that allowed for an effective dissipation of metabolic heat through evaporation.

However, the deviation of the RHF observed for the foundry workers from those predicted by the RSR or PHS models did not significantly alter the paradigm of heat flow development on the skin or impact on the validity of the heat strain evaluation for these workers. As the magnitude of the RHF observed in this study constituted less than 5 % of the metabolic heat consumption, the change in the required sweat rate in response to a deviation of up to 14 % in RHF was less than 7 %. Furthermore, the prediction of E_p , w_p , and Sw_p was practically not influenced by the RHF deviation, possibly as a result of thermo-physiological constraints being considered when these parameters of physiologically achievable heat strain were determined. For example, in the RSR model the w_p could not exceed the maximum skin wettedness when applied in calculating the E_p and Sw_p . The required heat strain as predicted by the PHS model was less affected by the deviation in RHF than those predicted by the RSR model.

The uncertainty involved in the application of the C_{res} and E_{res} approximations to local populations could also arise when the physiological quantities used in the approximation were different from those referenced in the approximation. For example, Livingstone et al. (1994) in Canada investigated the

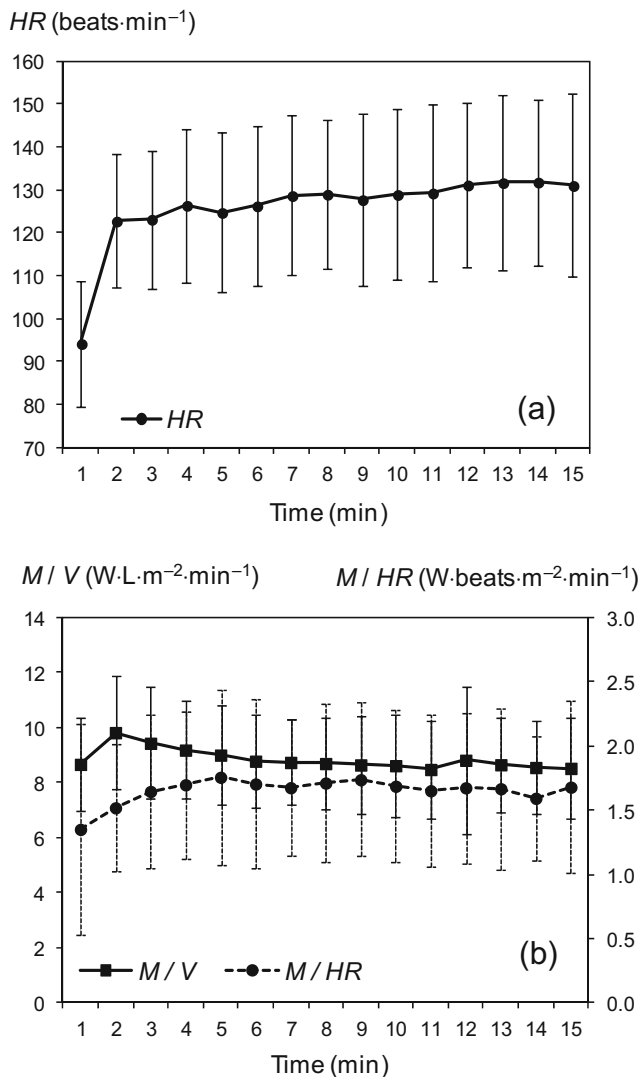


Fig. 6 Change in **a** HR and **b** ratio of M to V (solid squares) and of M to HR (solid circles) among Taiwanese workers during the first 15 min of exercise in iron and steel plants. Data are mean \pm SD. M metabolic rate, V respiratory ventilation rate, HR heart rate

temperature of the respired air of subjects working on a treadmill at combinations of t_a (nominally 20, 30, 40, and 45 °C) and rh (20 and 100 %). A relationship between the respiratory ventilation rate L (L min⁻¹) and the production of metabolic heat MH (W) for the subjects, $L = 0.076 MH$ (or $MH = 13.2 L$), was derived from Livingstone et al. and used in the development of the $C_{res(PhS)}$ approximation in the PHS model (Malchaire et al. 2001). However, based on our data, for Taiwanese foundry workers a similar expression would have been $L = 0.126 MH$ (or $MH = 7.9 L$). Physiologically, this difference translates into a higher metabolic heat production per respiration volume for Taiwanese workers. Cain et al. (1990) in Canada investigated in an environmental chamber the temperature and humidity of the expired air of subjects working under various levels of M at -40, -20, 0, and 20 °C, and reported that 25–30 % of the resting M and 15–

20 % of the working M were lost via respiration. In our study, the loss of respiratory heat (sum of $C_{res(TW)}$ and $E_{res(TW)}$) was less than 5 % of the working M for these foundry workers. These results demonstrated that a validation using local workers' data was essential for the successful application of RHF approximation to populations of varying heat strain capacities.

In our study, the validation of $C_{res(RSR)}$ and $E_{res(RSR)}$ approximations were also attempted by substituting a relationship $V/A_{Du} = (0.073 \pm 0.019) M$ as determined for Taiwanese workers into Eqs. (1) and (2), respectively, to obtain the $C_{res(RSR-Adj)}$ and $E_{res(RSR-Adj)}$ (Eqs. (15) and (16), respectively). The $C_{res(RSR-Adj)}$ and $E_{res(RSR-Adj)}$ predictions were well correlated to but different from the observed $C_{res(TW)}$ and $E_{res(TW)}$ values. Our finding suggested that the approach of validation in this attempt was not able to fully consider sources other than the V and M that might interfere the approximation, including the individual variation among the workers in metabolic heat production.

Conclusions

This study examined the validity of the RHF approximations in the RSR and PHS models using physiological measurements of heat-exposed Taiwanese foundry workers and then validated these approximations. In both models, the C_{res} prediction increasingly deviated from the observed value when the WBGT reached 35 °C. While the C_{res} and E_{res} approximations in both models presented a discrepancy of up to 3 and 11 %, respectively, the deviation of the RHF's observed for the workers from those predicted by the RSR or PHS models did not result in a significant change in the heat loss via the skin. Future research may focus on exploring techniques other than linear regression for application to validate the C_{res} and E_{res} approximations in the PHS model.

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Compliance with ethical standards The authors declare that the experiments conducted in the study comply with the current laws of the country in which they were performed. All procedures performed were in accordance with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The study participants were briefed on the purpose, design, and experimental procedures of the study. Informed consent was obtained from all individual participants included in the study. The research protocol and the informed consent form were reviewed and approved by the Research Ethics Committee of China Medical University and Hospital (CMUH102-REC3-006).

Conflict of interest The authors declare that they have no conflict of interest.

References

- Cain JB, Livingstone SD, Nolan RW, Keefe AA (1990) Respiratory heat loss during work at various ambient temperatures. *Respir Physiol* 79:145–150
- Chen ML, Chen CJ, Yeh WY, Huang JW, Mao IF (2003) Heat stress evaluation and worker fatigue in a steel plant. *Am Ind Hyg Assoc J* 64(3):352–359
- Fukazawa T, Havenith G (2012) E-2 Ethnic differences in thermal responses and comfort sensation between Japanese and Caucasian young males under a temperate environment. In: Proceedings of the 36th Symposium on Human-Environment System (HES36). Japanese Society of Human-Environment System, Nagoya, Japan, December 1–2, 2012, pp. 165–168
- Havenith G, van Middendorp H (1990) The relative influence of physical fitness, acclimatization state, anthropometric measures and gender on individual reactions to heat stress. *Eur J Appl Physiol* 61:419–427
- ISO 7726 (1998) Ergonomics of the thermal environment—instruments for measuring physical quantities, 2nd edn. International Organization for Standardization, Geneva
- ISO 7730 (2005) Ergonomics of the thermal environment—analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local comfort criteria, 3rd edn. International Organization for Standardization, Geneva
- ISO 7933 (1989) Hot environments—analytical determination and interpretation of thermal stress using calculation of required sweat rate. International Organization for Standardization, Geneva
- ISO 7933 (2004) Ergonomics of the thermal environments—analytical determination and interpretation of thermal stress using calculation of the predicted heat strain, 2nd edn. International Organization for Standardization, Geneva
- ISO 8996 (2004) Ergonomics of the thermal environment—determination of metabolic rate, 2nd edn. International Organization for Standardization, Geneva
- ISO 9886 (2004) Ergonomics—evaluation of thermal strain by physiological measurements, 2nd edn. International Organization for Standardization, Geneva
- Livingstone SD, Nolan RW, Cain JB, Keefe AA (1994) Effect of working in hot environments on respiratory air temperatures. *Eur J Appl Physiol* 69:98–101
- Malchaire J, Piette A, Kampmann B, Mehnert P, Gebhardt H, Havenith G, Den Hartog E, Holmér I, Parsons K, Alfano G, Griefahn B (2001) Development and validation of the predicted heat strain model. *Ann Occup Hyg* 45(2):123–135
- Malchaire J, Kampmann B, Mehnert P, Gebhardt H, Piette A, Havenith G, Holmér I, Parsons K, Alfano G, Griefahn B (2002) Assessment of the risk of heat disorders encountered during work in hot conditions. *Int Arch Occup Environ Health* 75(3):153–162
- MOEA (2014) Department of Statistics: factory operation census database. Ministry of Economic Affairs, Taipei. <http://dmz9.moea.gov.tw/GMWeb/common/CommonQuery.aspx>. Accessed 3 February 2014
- MOL (1998) Standards of work-rest schedule for workers of high-temperature operations. March 25, 1998. Ministry of Labor, Taipei
- Parsons K (2013) Occupational health impacts of climate change: current and future ISO standards for the assessment of heat stress. *Ind Health* 51:86–100
- Varene P (1986) Computation of respiratory heat exchanges. *J Appl Physiol* 61:1586–1589
- Youle T, Parsons K (2009) The thermal environment (second edition 1996). Addendum to the second edition. Technical guide no. 12. British Occupational Hygiene Society, London