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Modelling of Energy Expenditure at Welding Workstations: Effect of Temperature on Work Performance

SA Oke, J.U. Obioma

Department of Mechanical Engineering
University of Lagos, Nigeria

sa_oke@yahoo.com

OG Akanbi, K Adekunle, FA Oyawale

Department of Industrial and Production Engineering,
University of Ibadan, Nigeria

Abstract

The welding workstation usually generates intense heat during operations, which may affect the welder's health if not properly controlled, and can also affect the performance of the welder at work. Consequently, effort to control the conditions of the welding workstation is essential, and is therefore pursued in this paper. This paper develops a mathematical model that maximises the work output while minimising energy consumption at the welding workstation. Particular emphasis is placed on the effect of temperature on work performance. The important principle of conduction is applied through the human flesh that experiences temperature changes at the welding workstation. The welder-environment interaction is investigated with a focus on the welder's link and their relationship with blood flow. The results show that the blood in the arteries loses heat to the blood in the veins, and is aided by convection in the veins. Further heat losses occur in the skin layer of fat and muscle, and finally to the air. The study hopes to stimulate greater productivity and optimised resource utilisation. Thus, the Safety, Health and Environment (SHE) manager can assist in controlling the surroundings for optimal welder's comfort.

Keywords: Welding, work conditions, work environment, temperature, blood flow

1 Introduction

Welding constitutes an important occupation, which is commonly performed in various manufacturing industries, and in many small-scale industrial enterprises. Traditionally, welding workstations (usually) generate high heat, and therefore become uncomfortable for humans to work at. As a result, there is need to understand the welder-work-environment interaction, and its relationship to temperature changes in both the environment and the welder's body.

Several accounts have been made in the literature on the welding workstation. Langus et al. (2007a) focus on a theoretical derivation of a general synergic equation of pulsed MIG/MAG welding with width-controlled sine-wave current pulses that relates a mean welding current with pulsed welding parameters. This work is further extended in a study that focuses on an analysis and optimisation of the material transfer through the

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arc using a limiting criterion determined by an isoparametric equation (Lanus et al., 2007b). From the above review, it seems that intellectual discussions relating to the welder's environment and the performance of the welder at work has not been addressed. This therefore calls for the need to investigate into this important area of research.

Since the current study is a crossbreed between welding and the scientific area of energy expenditure, related accounts on energy expenditure literature is given. From a brief overview of the energy expenditure literature, reports have been given on energy expenditure in industrial vacuum cleaners (Mangelkoch and Clark, 2006), long-haul cabin crew (Barnes, 1973), wildland fire fighters (Heil, 2002) and various work postures (Tarriere and Andre, 1970). For example, Mengelkoch and Clark (2006) evaluated two types of industrial vacuum cleaners in terms of energy expenditure using twelve industrial cleaners, performed two 1-h vacuuming tasks with an upright vacuum cleaner (UVC) and a backpack vacuum cleaner (BPVC). The results indicate that the BPVC experienced workers vacuumed at a cleaning rate 2.07 times greater than the UVC and had similar levels of energy expenditure compared to the slower cleaning rate with the UVC. Heil (2002) used an electronic activity monitor to estimate total energy expenditure in wildland fire fighters by focusing on ten Hot Shot fire fighters who worked for 21 consecutive days. The reported results agreed with the literature and suggest that the electronic activity monitor provided reasonable estimates of energy expenditure in wildland fire fighters. From this additional review, it seems obvious that evaluating the energy expenditure at welding workstations is still open to investigation.

The welder energy expenditure problem is concerned with what amounts of energy should the welder expend in a way that maximises his work output while controlling the effect of environmental temperature on performance. A survey of the literature seems to indicate that no previous attempt has been made to model the problem using the principle of conduction that is applied through the human flesh which experiences temperature changes at the welding workstation. In this paper, a mathematical approach is undertaken to conceptualise the effect of temperature on work performance, using the principle of conduction with one-dimensional steady conduction applied through the human flesh. The welder-work environment interaction is analysed with consideration for welder's limbs and their relationship with blood flow. This research grew out of the need to contribute to the recent intellectual discussions that tend to promote activities within small and medium scale enterprises.

2 Methodology

The methodology used in studying the welder-environment interaction is to visualize this system as a process, which involves transfer of heat by a suitable method from the environment to the human body (welder). Based on the understanding of thermodynamic principles, the process of heat transfer is assumed to follow conduction principles. An important principle in conduction, which could readily match the phenomenon being investigated, is the Fourier law of conduction. For one-dimensional steady conduction through the human flesh, $\dot{Q} = -kA\left(\frac{dT}{dx}\right)$. (1)

This relationship was stated by Rogers and Mayhew (1980). The components of this expression are stated as follows:

$\dot{Q}$ = rate of heat flow from the environment to the human body measured in J/s(W)

k = thermal conductivity W/mK, and A = area of flow m^2

$\frac{dT}{dx}$ = temperature gradient with respect to the thickness of the skin k/m

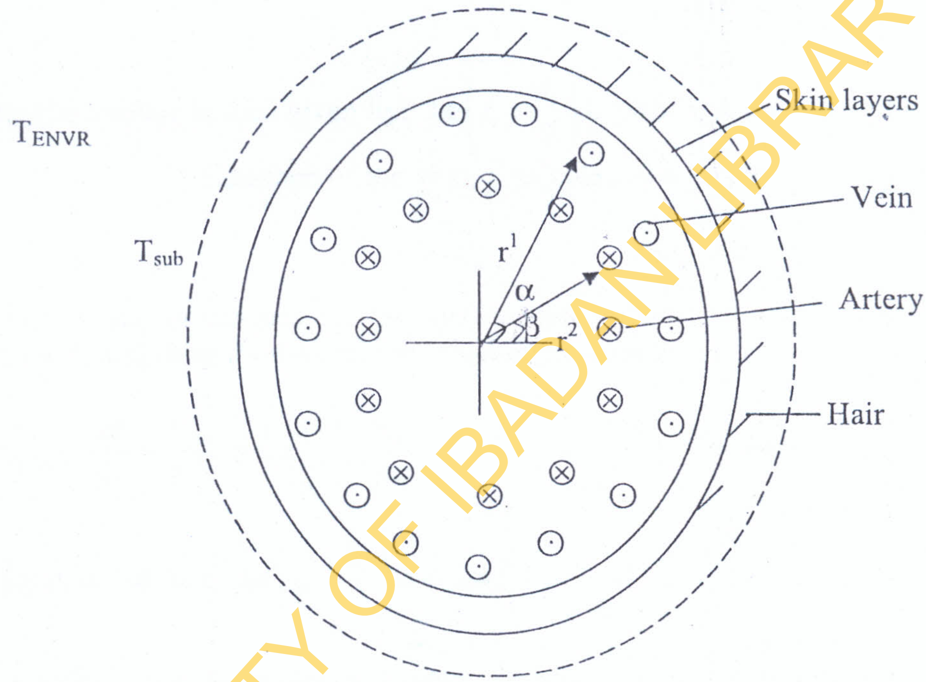
The idea utilised in this work is that the phenomenon of heat flow from the environment or hot water to a solid metallic body, which conducts heat, is similar to that of heat flow from the welding environment to the human body since the human body also experiences heat and reacts in a similar way as a metallic object does. By applying this idea to humans, it is assumed that heat flow from a hot environment to the human body (assumed to be at room temperature) will constantly increase, and pass through the layers of the skin. It is expected that the outer layer of the skin will be the first to absorb heat, which gradually passes to the inner parts. Since different metals have different rates of absorbing heat, their specific thermal conductivity is different. However, it is the same for all humans since the body is made up of the same materials. The specific thermal conductivity of the human welder is a measure of the property of the human body that allows it to conduct heat. The measure of area as expressed above relates to the area of the skin that has contacts with flow of heat (area of flow). Since the skin consists of different layers and the temperature of the different layers at any particular time differs as a result of environmental heat, it is expected that a profile exists which shows the variation, referred to as temperature gradient in the human body. Thus, equation (1) is a holistic relationship including the rate of heat flow from the environment to the human body, the thermal conductivity of the human body, the area of contact or flow of heat in the body, and the temperature gradient in terms of heat absorbed in the human body.

Equation (1) could be transformed into a differential equation of three-dimensional conduction properties as follows $\frac{1}{K}\left(\frac{\partial T}{\partial t}\right)=\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}+\frac{\dot{q}_g}{k}$ (2)

These authors defined the following components: $K=\frac{k}{\rho c_p}$ thermal diffusivity $\left[\frac{\text{length}^2}{\text{time}}\right]$ m^2/s. Note that k = thermal conductivity W/mK, ρ = average density of the human body kg/m^3, c_p = specific heat capacity of the human body J/kgK, and $\dot{q}_g$ = rate of heat generated by unit volume.

Equation (2) is a partial differential equation of the second order, which could also represent the relationship between the above-mentioned elements, but with specification along three dimensions (i.e. x, y, and z). The equation could be related to definitions given by Rogers and Mayhew (1989). In addition, thermal conductivity and specific capacity of the human body are related to those specified by Rogers and Mayhew (1980), and form an important element in the mechanics of flow discussed in this work. Also, the rate of heat generated is specified in volume since volumetric measures of blood and condensed heat (air) could be made.

While considering one-dimensional flow, the human limb will be modelled as follows. The limb will be visualised as consisting of layers of different components (Figure 1). The first layer being the hair, followed by the skin then the veins, which lie just beneath the skin then, the arteries which are further embedded in the human flesh.



⊙ Vein blood flow out of paper

⊗ Artery blood flow into paper

Figure 1. Cross-section of Welder's Limb

It is assumed that there is good thermal contact for conduction to take place. Due to the biological and physiological processes, heat is generated internally and distributed by the blood in the arteries. The temperature of the blood of the artery will serve as the body temperature that determines what signals are sent to the brain. The veins and arteries will be produced as pipe-conveying systems at different temperatures. The temperature very close to the skin will be slightly different from the environmental temperature since the hairs trap a layer of air there (Barnes, 1973). Polar coordinates will be used. Hence, a point in the cross-section will be p(r, θ). Invoking the continuum hypothesis, the veins and arteries form cylindrical surfaces concentric with the axis of the limb. If n is the number of veins and d_{mean} is the mean diameters of the veins, $nd_{mean} = 2\pi r_1$ (3)

where r_1 is the radius from the axis of the limb to the center of the vein. Similar arguments can be used for the arteries: $md_2 = 2\pi r_2$ (4)

where m = no. of arteries, d_2 = mean diameter of arteries, and r_2 = radius from limb axis to the center of the artery

If the ratio of arteries to veins be γ, then $\frac{n}{m} = \gamma$ or $n = m\gamma$. By referring to equations (3) and (4), and retaining their right hand side expressions while substituting the symbol for the ratio of arteries to veins, we have:

$$\left.\begin{matrix} \gamma m d_1 = 2\pi r_1 \\ m d_2 = 2\pi r_2 \end{matrix}\right\} \quad (5)$$

The area for the surface is then given by: $2\pi\left(r_1 + \frac{d_1}{2}\right)L$, where L represents the length of the veins. For the outer surface of the vein, a calculation is made using equation (5) to obtain $d_1 = \frac{2\pi r_1}{\gamma m}$.

From the expression for the area for the surface stated above, we could substitute the expression for d_1 and simplify to obtain the final expression as

$$\text{Area} = 2\pi\left(r_1 + \frac{2\pi r_1}{\gamma m} \times \frac{1}{2}\right)L = 2\pi\left(r_1 + \frac{\pi r_1}{\gamma m}\right)L = 2\pi r_1\left(1 + \frac{\pi}{\gamma m}\right)L \quad (6a)$$

Likewise for inner surface, $2\pi\left(r_1 - \frac{d_1}{2}\right)L = 2\pi r_1\left(1 - \frac{\pi}{\gamma m}\right)$ (6b)

Thus, we conclude that the outer and inner surface area for the arteries is given as $2\pi\left(r_2 + \frac{d_2}{2}\right)L$ (i.e outer) and $2\pi\left(r_2 - \frac{d_2}{2}\right)L$ (i.e. inner), respectively.

Using equation (5), it is understood that $2\pi r_2\left(1 + \frac{\pi}{m}\right)$ and $2\pi r_2\left(1 - \frac{\pi}{m}\right)$ are the needed terms, which give rise to equation (7)

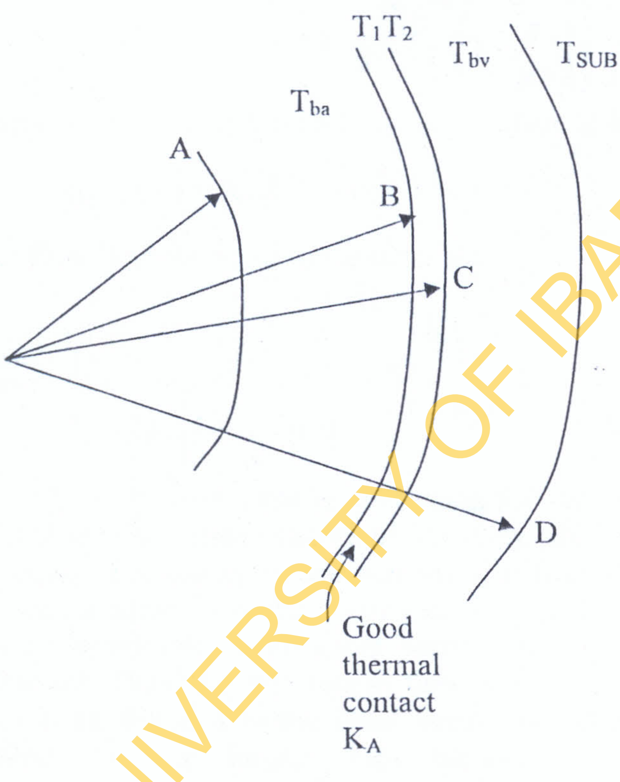
From Fourier's law, using equation (1), the expression for area could be substituted in 'A', with 'T' differentiated with respect to 'r' as: $\dot{Q} = -K2\pi r L\left(\frac{dT}{dr}\right)$

By taking the limits of integral from $r = r_1$ to $r = r_{limb}$, we have $\dot{Q}\int\frac{dr}{r} = -K2\pi L\int dT$. This reduces to $\dot{Q}\ln r = -K2\pi LT + Const$. Further analysis yields

$\dot{Q}(\ln r_2 - \ln r_1) = -K2\pi L(T_2 - T_1)$, which reduces to $\dot{Q}\ln\frac{r_2}{r_1} = -K2\pi L(T_2 - T_1)$, and

finally, $$\dot{Q} = \frac{-2\pi KL(T_2 - T_1)}{\ln\left(\frac{r_2}{r_1}\right)} \qquad (8)$$

As derived by Rogers and Mayhew (1980), the concentric layers of veins and arteries are as shown in Figure 2.



$$A = r_2\left(1 - \frac{\pi}{m}\right)$$

$$B = r_2\left(1 + \frac{\pi}{m}\right)$$

$$C = r_1\left(1 - \frac{\pi}{\gamma m}\right)$$

$$D = r_1\left(1 + \frac{\pi}{\gamma m}\right)$$

T_{ba} = temperature of blood in artery
T_{bv} = temperature of blood in vein
T_{SUB} = temperature very near the skin due to the stagnant air caused by the hairs, similar to a boundary layer.

Figure 2. Concentric layers of veins and arteries

From Figure 2, it seems that relationships among (A, r_2, π, and m), (B, r_2, π, and m), (C, r_1, π, γ and m), and (D, r_1, π, γ and m) could be stated as shown above. The temperature of the blood in the arteries loose heat to the blood in the veins aided by convection in the veins. Further heat losses occur in the skin layers of fat and muscle, finally to the air. In the absence of artificial or forced convection such as an industrial blower, the air is stagnant.

Heat flow from the blood in the arteries to the adjacent flesh is given by:

$$\dot{q}_1 = -\alpha_{ca}\left(T_1 - T_{ba}\right) - \alpha_{ra}\left(T_1 - T_{ba}\right)$$

$$= -\left(\alpha_{ca} + \alpha_{ra}\right)\left(T_1 - T_{ba}\right) \times 2\pi r_2 \left(1 + \frac{\gamma}{m}\right) L$$

where α_{ca} = convection heat transfer coefficient W/m2K

α_{ra} = radiation heat transfer coefficient

Heat flow from the walls of the arteries to the walls of the veins will be given by:

$$\dot{q}_2 = \frac{-2\pi K_A L\left(T_2 - T_1\right)}{\ln\left[\frac{C}{B}\right]} = \frac{-2\pi K_A L\left(T_2 - T_1\right)}{\ln\left[\frac{r_1\left(1 - \frac{\pi}{\gamma m}\right)}{r_2\left(1 + \frac{\pi}{\gamma m}\right)}\right]} \quad (10)$$

From equation (9), heat flow from vein surface to blood in the veins:

$$\dot{q}_3 = -\left(\alpha_{cv} + \alpha_{rv}\right)\left(T_{bv} - T_2\right) \times 2\pi r_1 \left(1 + \frac{\pi}{\gamma m}\right) L \quad (11)$$

Heat flow from the veins to the outer skin, $\dot{q}_4 = U\left(T_{SUB} - T_{bv}\right)$

$$\text{where } \frac{1}{U} = \frac{1}{2\pi r_1\left(1 + \frac{\pi}{\gamma m}\right) L\alpha_v} + \sum_{i=3}^{n} \frac{\ln\left(\frac{r_i}{r_{i-1}}\right)}{2K_i \pi L} + \frac{1}{2\pi r_{limb}} L\alpha_{air} \quad (12)$$

where U is the heat transfer coefficient for the skin layers between the veins and the outer skin. The various shapes of our body parts are circular, tapering from one end to the other. For example, consider the arm from the ball and socket joint to the wrist. This has a tapered circular shape from the upper part of the arm to the wrist. As such, when viewed from a cross-cut section, it consists of concentric circles of various diameters. Thus, the assumption that many parts of the human body are circular and taper from one end to the other holds true. Other parts of the body that share this attribute are our fingers, legs, trunks, abdomen and neck. If we consider a diagrammatical representation of the cross-section of the human hand, for exámple, it is seen that it consists of concentric circles of radius r_i (at the outermost part of the body), radius r_{i-1} (at the next inner circle), radius r_{i-2} (at a further circle inside), r_{i-3}, r_{i-4}, etc. at further movements into the inner parts of the concentric circles. This description is true for many parts of the body. Figure 1 therefore illustrates these concentric circular characteristics of the various parts of the body with an example drawn from the arm or hand.

Heat transfer is a property of fluid, which reflects the capacity to conduct and radiate heat. It is commonly used in fluids computations and now adapted to the conduction and radiation of heat in the human body. The conduction and radiation properties of heat in the human body are categorized as convection and radiation. These are represented as α_{cv} and α_{rv}, respectively. Thus, the heat transfer is considered for the

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skin layers between the veins and the outer skin. Thus, mathematically, the relationship among αv, α_{cv} and α_{rv} is a simple additive given as:

$$\alpha_v = \underbrace{\alpha_{cv}}_{\text{convection}} + \underbrace{\alpha_{rv}}_{\text{radiation}}$$

Notice that α_v is referred to as the total surface heat transfer coefficient for the vein.
Note that k_i = thermal conductivity of the i^{th} layer, and r_{limb} = radius of the limb.
If r_i = outer radius of the i^{th} skin layer, and
r_{i-1} = outer radius of the skin layer before the i^{th} skin layer, then some understanding of Figure 3 could be made.

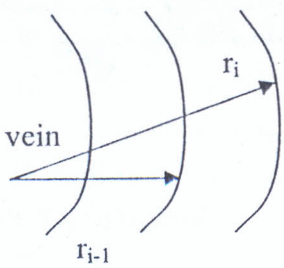

Figure 3. Concentric circular attribute representation of the human hand (relationship between skin layers and veins)

$$\alpha_{air} = \alpha_{cair} + \alpha_{rair}$$

Total surface heat transfer coefficient for outer skin surface in contact with stagnant air may be mathematically expressed as - $(T_1 - T_{ba}) - (T_2 - T_1) - (T_{bv} - T_2) - (T_{SUB} - T_{bv})$. If this expression is expanded and the terms put together, it reduces to - $(T_{SUB} - T_{ba})$.By considering the right hand side of equation (13), it could be observed that the terms T_{SUB} and T_{ba} have earlier been expressed in terms of

$$\frac{\dot{q}_1}{2\pi r_2\left(1+\frac{\pi}{m}\right)L\alpha_{ca}+\alpha_{ra}} + \frac{\dot{q}_2}{2\pi K_A L}.\ln\left[\frac{r_1\left(1-\frac{\pi}{\gamma m}\right)}{r_2\left(1+\frac{\pi}{m}\right)}\right] + \frac{\dot{q}_3}{2\pi r_1\left(1-\frac{\pi}{\gamma m}\right)L\alpha_{cv}+\alpha_{rv}} + \frac{\dot{q}_4}{U} \qquad (14)$$

If $\dot{q}_1 = \dot{q}_2 = \dot{q}_3 = \dot{q}_4 = \dot{q}$

$$(T_{SUB} - T_{ba}) = \dot{q}\left[\frac{1}{\alpha_a} + \ln\frac{\left[\dfrac{r_1\left(1 - \dfrac{\pi}{\gamma m}\right)}{r_2\left(1 + \dfrac{\pi}{m}\right)}\right]}{2\pi\pi_A L} + \frac{1}{\alpha_v} + \frac{1}{U}\right] \qquad (15)$$

where $$\frac{1}{U} = \frac{1}{2\pi r_1\left(1 + \dfrac{\pi}{\gamma m}\right)L\alpha_v} + \sum_{i=3}^{n}\frac{\ln\left(\dfrac{r_i}{r_{i-1}}\right)}{2K_i\pi L} + \frac{1}{2\pi r_{limb}}L\alpha_{air} \qquad (16)$$

If the heat flow is steady, $\dot{q}_1 = \dot{q}_2 = \dot{q}_3 = \dot{q}_4$, these equations (9), (10), (11) and (12) are equal. But if the heat flow is not steady, then $\dot{q}_1$, $\dot{q}_2$, $\dot{q}_3$ and $\dot{q}_4$ may not be equal. Next, how do we relate T_{ba} in equation (9) and T_{SUB} in equation (12)?

$$\left.\begin{aligned}
\dot{q}_1 &= -(\alpha_{ca} + \alpha_{ra})(T_1 - T_{ba})\,2\pi r_2\left(1 + \frac{\pi}{m}\right)L \\
\dot{q}_2 &= \frac{2\pi\pi_A L}{\ln\left[\dfrac{r_1\left(1 - \dfrac{\pi}{\gamma m}\right)}{r_2\left(1 + \dfrac{\pi}{m}\right)}\right]} \\
\dot{q}_3 &= -(\alpha_{cv} + \alpha_{rv})(T_{bv} - T_2)\times 2\pi r_1\left(1 - \frac{\pi}{\gamma m}\right)L \\
\dot{q}_4 &= U\,(T_{SUB} - T_{bv})
\end{aligned}\right\} \qquad (17)$$

$$T_{ba} - T_{SUB} + \dot{q}\left\{\frac{1}{\alpha_a}\cdot\frac{1}{2\pi r_2\left(1 + \dfrac{\pi}{m}\right)L} + \frac{\ln\left[\dfrac{r_1\left(1 - \dfrac{\pi}{\gamma m}\right)}{r_2\left(1 + \dfrac{\pi}{m}\right)}\right]}{2\pi K_A L} + \frac{1}{\alpha_v}\cdot\frac{1}{2\pi r_1\left(1 - \dfrac{\pi}{\gamma m}\right)L}\right.$$

$$+\frac{1}{2\pi r_1\left(1+\frac{\pi}{\gamma m}\right)L\alpha_v}+\sum_{i=3}^{n}\frac{\ln\left(\frac{r_i}{r_{i-1}}\right)}{2\pi K_i L}+\frac{1}{2\pi r_{limb} L\,\alpha_{air}}\Bigg\}$$

$[i = 3, 4, \ldots, n]$

when $i = 3$, $r_{i-1} = r_2 = r_2\left(1+\frac{\pi}{m}\right)$ (18)

This equation can be used to determine the temperature of the blood in the artery given the temperature in the boundary layer of the outer skin usually measured by a thermometer given the rate of heat transfer.

Finally, $$T_{SUB} - T_{ENVR} = -\frac{\dot{q}}{\alpha_{ENVR}} \quad (19)$$

3 Case study

The University of Lagos, Faculty of Engineering welding shop is an experimental laboratory for the training of undergraduate engineering students in 4 courses of workshop practice I, II, III and IV. The workshop also serves as a service center to the university by providing welding services of building house gates, burglar proofs, and other metallic structures that may be requested. Consequently, in many instances, the work operations are demanding, and the environment under which the various tasks are performed is sometimes under high temperatures such that the jobs done may take several days to complete. In such cases, an understanding of the relationship between environmental temperature readings and its effect on welder's performance at work is necessary. Thus, the current work takes an ergonomic viewpoint of the problem. Based on this scenario, some hypothetical data were simulated to mimic real life data in order to test the model.

The first set of data relates to the limb, veins and arteries. Here, the radius of the limb, r_{limb}; mean radius of veins, r_1; and mean radius of arteries, r_2. These are 0.05m, 0.045m and 0.03m respectively. The ratio of the veins to arteries is also of importance to model testing. This is given a value of $\gamma = 10$. Additional information required to test the model include number of arteries cross-section, length of limb considered, and the film coefficient for arteries walls and vein walls respectively. These are given as $m = 12$, $L = 0.2$m, $\alpha_a = 10\text{kw/m}^2\text{k}$, and $\alpha_v = 10\text{kw/m}^2\text{k}$ respectively.

Other information needed for model verification include thermal conductivity of tissue between arteries and veins, inner and outer radius of fatty layer, as well as inner and outer radius of epidermis. These are given as $k_A = 10$w/mk, $r_2 = \left(1+\frac{\pi}{m}\right)$, $r_3 = 0.048$m, and $r_4 = 0.049$m respectively. Although in this computation, other layers are neglected, in others, it may not. Neglect of other layers is for the purpose of avoiding computational complexity. Further information required in the model verification include thermal cónductivity of fatty layer and epidermis and film coefficient of sub-layer (air). The values simulated for usage are $k_3 = 0.5$w/mk, $k_4 = 0.7$w/mk and $\alpha air = 0.1kw/m^2k$ respectively. In solving the problem with the above data, the use of equation (19) is made with the components calculated from previously derived expressions. Thus, $T_{ba} - T_{sub}$ is calculated as:

$$\dot{q}\left[\frac{1}{10{,}000}\cdot\frac{1}{2\pi\times0.03\times\left(1+\frac{\pi}{12}\right)0.2}\right]+\frac{\mathrm{In}\left[\frac{0.045\left(1-\frac{\pi}{10\times12}\right)}{0.03\left(1+\frac{\pi}{12}\right)}\right]}{2\pi\times10\times0.2}$$

$$+\frac{1}{10{,}000}\cdot\frac{1}{(2\pi\times0.045)\times\left(1+\frac{\pi}{12}\right)0.2}+\frac{1}{2\pi\times0.045\times\left(1+\frac{\pi}{10\times12}\right)0.2\times10{,}000}$$

$$+\frac{\mathrm{In}\left[\frac{0.048}{0.03\left(1+\frac{\pi}{12}\right)}\right]}{2\pi\times0.5\times0.2}+\frac{\mathrm{In}\left[\frac{0.049}{0.048}\right]}{2\pi\times0.7\times0.2}+\frac{1}{2\pi\times0.05\times0.2\times100}$$

This gives summarized values of:

$$\dot{q}\left[0.0021+0.12+0.0018+0.0017+0.378+0.023\right]$$

Thus, $T_{ba} - T_{sub} = 0.6866q \approx 0.7\,\dot{q}\,^{o}C$

From the literature, it is assumed that 10ml of sweat evaporates in 200min due to the heat transferred. However (Rogers and Mayhew, 1980), mass = ρv = $1000 \times \frac{1}{10{,}000}$ = 0.001kg of sweat in 20mins. The latent heat of evaporation = 2256kT/kg. Thus, $\dot{q} = 2256\times1000\times0.001\times\frac{1}{20\times60}$ = 1.88W. Therefore, $T_{ba} = T_{sub}$ = 0.6866 x 1.88 = 1.29°C. Thus, a difference of about 1.29°C exists between the temperature of the blood in the arteries and the temperature of the boundary layer that is close to the skin. The implication of this outcome is that to stay healthy, this difference must be kept as minimum as possible, otherwise a situation may arise such that the welder suddenly collapses at work without advance warning or signals.

4 Conclusion

With the increasing efforts of stakeholders in the welding industry to provide an ergonomic environment, where the welder works at optimum productivity, there is a need to mathematically quantify the relationship among the variables involved in welding operations at the various postures of the welder. This has necessitated the development of a framework in which the welder's body (skin) is considered as a boundary. It absorbs heat from the surroundings and this heat is related to the working process of the blood in the arteries of the human body. Based on the model developed, a verification exercise was carried out in which simulated values were used to test the model variables. Mean radius, ratio of what, number, length, thermal conductivity coefficients of the welder's limb, veins, arteries, tissue, epidermis and air are the primary variables that serve as input in calculating the temperature of the blood in the artery (T_{ba}) and the temperature very near the skin due to the stagnant air caused by the hairs (T_{sub}). This is similar to a boundary layer.

From the investigation, it was observed that the difference between T_{ba} and T_{sub} is vital to the well-being of a welder. If the value of T_{sub} is too high, it is possible that T_{ba} may increase due to reversal of heat flow. This may increase due to reversal of heat flow which may be dangerous for living tissue. On the other hand, if T_{sub} is too low, the body may not be able to maintain T_{ba} which may lead to hypothermia. Hence, controlling the rate of heat flow may be the key in ensuring the welder's comfort. This can be achieved in numerous ways, by controlling the components of the equation. For example, using a fan can affect $\alpha_{c\ air}$, which is a component of α_{air}, and thus affect the temperature drop. Other methods may be developed by considering equation (18). Finally there are numerous aspects of the study that need future considerations. For example an immediate study on sensitivity analysis of the model variables is necessary. This would reveal what variables are sensitive to small changes in values, and which variables are not. A follow-on study may be model validation. With these investigations, a wide research opportunity would be opened up for researchers.

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