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A THERMODYNAMIC APPROACH TO THE MICROCLIMATE ENVIRONMENT OF MUSEUMS

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Abstract

Historical buildings represent an important part of the cultural heritage and an economic source for Countries. Generally, they are used for public purposes and specifically to host museums and art exhibitions. Even if they are private homes, these buildings must be conserved in their original conditions as possible but have also to guarantee the best preservation conditions for the works of art they contain and a suitable thermal comfort for visitors and people living or working there. Therefore, a technical physical application of thermal comfort control is needed since the human thermal environment is the result of the interaction of air temperature, air velocity and humidity. These parameters are the basis of the designing of comfortable habitat.

Thermodynamics plays a key role in the analysis of systems in which energy transfer and energy transformation take place. In this contribution, a second law analysis of the thermal behaviour of the metabolism of a human body under environment changes is analysed by means of the extremum entropy generation. The result is that a change in room temperature affects hardly the metabolism. Consequently, thermal and hygrometric control must be developed in historical buildings with particular concern to the stationarity of the heating systems, in order to advantage the visitors.

The notions of entropy and its generation are the fundamentals of modern technical and engineering thermodynamics and thermal engineering. Entropy has been proved to be a quantity describing the progress of irreversible processes. Entropy generation allows to describe any irreversible process without mathematical constrains (linear or nonlinear phenomena, open, closed or isolated systems), becoming a very interesting quantity in applications. We prove the usefulness of the entropy generation extremum principle to evaluate the condition of the best comfort in historical buildings.

Keywords: microclimate, historical building, entropy, exergy

1. Introduction

Museums, art exhibitions and historical buildings, summarized as art buildings, represent both the man sign in history and an economic source for many countries. These places need both thermal and hygrometric controls in order to allow the visitors to enjoy their tour. Consequently, in addition to the diagnostics, preservation and restoration issues concerning both works of art and art buildings, the art is not only the result of a cultural path, but it is also a technical physical subject, based on the interaction between people and building's environment and the control of the building thermal comfort.

The human thermal environment is the result of the interaction among air temperature, air velocity and humidity. In order to design a comfortable environment, it is necessary to evaluate the effect of the combination of the thermal and hygrometric conditions on the person (the visitor) [1]. In the art buildings these conditions depend also from the number and the frequency of people inside the building itself. Modern indoor design methods are based on the heat exchange analysis of the human body and a lot of models are used to design the comfort assessment.

Thermodynamics plays a key role in the analysis of systems in which energy transfer and energy transformation take place. Near thermodynamic equilibrium, it is well known that the constitutive equations of motion can be obtained by using the variational principle of least dissipation [2-5] and the unique steady state can be found by minimizing the entropy production under some physical constraints [6]. By using other constraints, the constitutive equations of motion and the steady state can be found, respectively, by maximizing the entropy production [7-9]. The situation far from thermodynamic equilibrium, with non-linear dynamics and non-linear response, is much more difficult.
From the conservation of energy, both the system and its surroundings are increasing in entropy, which means decreasing the available energy, when mutual differences in energy densities are levelling off as a result of the processes [10]. The driving force of any process is the free energy [11], known also as exergy [12,13], including any external influx and work. The total force, when positive, makes the production a probable process; the energy flow is, statistically speaking, always downhill. According to this natural approach, all processes must follow the law of energy dispersal [14].
The notions of entropy and its generation are the fundamentals of modern technical and engineering thermodynamics [15] and thermal engineering. Entropy has been proved to be a quantity describing the progress of irreversible processes. Entropy generation allows to describe any irreversible process without mathematical constrains (linear or nonlinear phenomena, open, closed or isolated systems), becoming a very interesting quantity in applications [16].

2. Bioengineering thermodynamics and comfort

The researchers in the field of comfort for indoor environment tend to adopt the indoor volume as a reference for their analysis, probably because of the subjective point of view as users [17, 18]. Paradoxically, this approach uncouples the physics of human body, living indoor, from the physical characteristics of the building, because the quantities describing the performance of them are not the same quantities included in the classical comfort models. These latter quantities, for example the PMV (Predicted Mean Vote), the PPD (Predicted Percentage of Dissatisfied), the MET unit for metabolism, the CLO unit for clothing, considered in the standard ISO7730, are based on statistical observations of the relation between subjective response and objective environmental parameters, but cannot be incorporated in a balance of the living system, the human body, in its physical relation with the environment. In order to develop a unified, multi-scale approach, it is possible to leverage the physics of interactions and fluxes under a second law approach.
All the thermodynamic schools agree that for an adiabatic closed system (usually named isolated systems), its entropy increases during changes inside the system [19].
Now, we consider a natural system. It can change heat and mass with its environment. So, it is an open system which interacts with its environment [20]; it can be a simple or complex system too. We consider the environment as a thermostat [21, 22]. Considering the system together with its environment, we are analyzing an adiabatic closed system, so the entropy variation for the considered volume is maximum at the equilibrium, so allowing us to state that the flows between the open system and its environment cause the entropy generation rate density, the interaction between system and environment being responsible of irreversibility: without interaction, no irreversibility occurs.
Buildings and people living indoor can be thus analyzed from a natural point of view [23] based on a buildings bio-engineering thermodynamics [24]. In order to live, the human body convert its metabolism into its energy needs and it is possible to develop a second law analysis evaluating its exergy [1] as shown in the next sections.
The concept of exergy, which is derived by combining the energy and entropy balance equations together with environmental temperature, indicates the ability of energy and matter to make dispersion occur relative to their environmental space. The general form of exergy balance equation for a system in question is expressed as follows: [Exergy Input] - [Exergy Consumed] = [Exergy Storage] + [Exergy Output]. The unique feature of this balance equation is that there is the term of "consumed". Also unique is that, in the other three terms, there are either of "warm" or "cool" exergy together with either of "wet" or "dry" exergy depending on the indoor and outdoor conditions of temperature and water vapour pressure.

A correct evaluation of the human body exergy balance depends on the knowledge of T_{sk}, the skin temperature, and of T_0, the effective temperature of the environment, and not only of indoor air temperature, T_a. T_0 depends on the position of the human body in the indoor environment. Some technological improvements are needed in the sensors field in order to have exact reading of these variables.

In the recent past, few exergy balances of the human body have been deduced [1, 25, 26]. Different levels of complexity among them range from the 1-node model of Prek [1], to the 2-nodes model of Shukuya [26] and of Wu [27], to the 15-nodes model of Mady [28]. In those works, the minimum exergy consumption of the human body was derived. Some of them compared minimum of exergy consumption, i.e. maximum thermodynamical efficiency of human body, with subjective thermal sensations, basing on record from previous researches. Schweiker and coworkers [29] found that the operative temperature leading to the minimum of human body exergy consumption rate resulted to be around PMV values of -0.5. This is in line with other applications of the exergetic comfort model, as e.g. by Simone et al. [30], who found that the lowest exergy consumption rate is closer to a slightly cool thermal sensation. Similar considerations were derived both for hot and cold seasons [31].

A second law approach has been more often applied to systems and services than to human body, yet seldom implemented [32].

3. First law analysis of the human body

Life is an integrated process which involves nested living systems (complex systems of basic materials, cells, organisms and ecosystems) and their environments: a continuous interaction exists between living systems and environment both in time and in space [33]. Consequently, living systems have been defined as open systems with life-processes, that consist in capturing exergy, in exergy storage [34], in entropy exchange, in autopoietic processes [33]. Fanger [35] developed a steady state model based on the hypothesis that the body is in thermal equilibrium with negligible heat storage [1]: this model does not consider vaso-regulation and shivering because the body core and the skin are considered as just one compartment. The power balance of the thermal physiology of the human body, at the steady state, can be simplified as follows:

$$\dot{M} - \dot{w} = \left(\dot{q}_c + \dot{q}_{c,res}\right) + \dot{q}_r + \left(\dot{q}_e + \dot{q}_{e,res}\right) \tag{1}$$

where *M* is the metabolism (J/kg), *w* is the specific work (J/kg), *q* is the specific heat lost (J/kg), the subscript *c* means convective, *r* radiative, *e* evaporative, *res* respirative and *cr* core body. The indoor comfort analysis must consider also the transient condition and the time useful to reach a new comfort steady state. To this aim, it is necessary to introduce the heat storage, q_{cr}, in the core compartment and the heat storage in the skin, Q_{sk},, for which the following equations hold:

$$\begin{cases} \dot{Q}_{cr} = m_b\left[\dot{M} - \dot{w} - \left(\dot{q}_{c,res} - \dot{q}_{e,res}\right)\right] - \dot{Q}_{cr-sk} = \left(1-\alpha\right)\dfrac{mc_b}{A_{Du}}\dfrac{dT_{cr}}{dt} \\ \dot{Q}_{sk} = \dot{Q}_{cr-sk} - m_b\left(\dot{q}_c + \dot{q}_r + \dot{q}_e\right) = \alpha\dfrac{mc_b}{A_{Du}}\dfrac{dT_{sk}}{dt} \end{cases} \tag{2}$$

where Q_{cr-sk} is the heat exchanged from the body core and the skin [1]:

$$\dot{Q}_{cr-sk} = \left(k + \dot{m}_{bl}c_{bl}\right)\left(T_{cr} - T_{sk}\right) \tag{3}$$

where $\dot{m}_{bl}$ is the blood flow, *c* is the specific heat ($Jkg^{-1}K^{-1}$), *b* means body and *bl* blood, *k* is the thermal conductivity ($Wm^{-1}K^{-1}$), *T* is the temperature, A_{Du} is the surface body area (m^2) evaluated by means of the DuBois and DuBois formula [36]:

$$A_{Du} = 0.202 \cdot y_b^{0.725} m_b^{0.425} \tag{4}$$

where y_b is the height (m), m_b in the mass (kg) and α is the relative mass of the skin [37]:

$$\alpha = 0.0418 + \frac{0.745}{3600 \cdot \dot{m}_{bl} - 0.585} \tag{5}$$

The body temperature can be evaluated as [38]:

$$T_b = \alpha T_{sk} + (1-\alpha) T_{cr} \tag{6}$$

Last, during respiration the body exchanges [1]:

$$\dot{Q}_{c,res} + \dot{Q}_{e,res} = 0.0014M(34 - T_a) + 0.0173M(5.87 - p_a) \tag{7}$$

The evaporated heat loss from the skin is the result of the combined action of the sweat secreted in consequence of the thermoregulatory control mechanisms and the spontaneous diffusion of water through the skin, whose body portion interested is evaluated as:

$$r_{rsw} = \frac{\dot{Q}_{rsw}}{\dot{Q}_{e,\max}} \tag{8}$$

where *rsw* means request sweating and the evaporative power loss [39] can be written as:

$$\dot{Q}_{rsw} = \dot{m}_{rsw} h \tag{9}$$

and the maximum power transfer due to evaporation is [38]:

$$\dot{Q}_{e,\max} = \frac{p_{sk,s} - p_a}{R_{cl} + \dfrac{1}{f_{cl} h_e}} \tag{10}$$

where f_{cl} is the correction factor for the increase in available surface area for heat exchange caused by clothing. Considering that only (1-w_{rsw}) fraction of the skin is covered by swat, the diffusive power loss results [38]:

$$\dot{Q}_{diff} = 0.06(1 - w_{rsw}) \dot{Q}_{e,\max} \tag{11}$$

with 0.06 the value of the skin wetness due to diffusion for normal indoor conditions. The evaporative power loss $\dot{Q}_e$ from the skin is the result of [38]:

1. the evaporation of sweat output for thermoregulation, $\dot{Q}_{rsw}$
2. the natural diffusion of water through the skin, $\dot{Q}_{diff}$

and therefore it follows:

$$\dot{Q}_e = \dot{Q}_{rsw} + \dot{Q}_{diff} \tag{12}$$

Moreover, respiration determines the loss of power $\dot{Q}_{res}$ for convection $\dot{Q}_{c,res}$ and evaporation $Q_{e,res}$ [38]:

$$\dot{Q}_{res} = \dot{Q}_{c,rsw} + \dot{Q}_{e,resf} = 0.0014M(34 - T_a) + 0.0173M(5.87 - p_a) \tag{13}$$

4. Second law analysis of the human body

In order to live, the human body convert its metabolism into its energy needs and it is possible to develop a second law analysis evaluating its exergy [1]:

$$Ex = H - H_0 \tag{14}$$

where H is the enthalpy and 0 labels the reference state. The thermal exergy exchanged through the skin can be written as:

$$Ex_{sk} = Ex_r + E_{th} \tag{15}$$

where Ex_r is the exergy for radiation:

$$Ex_r = \left(1 - \frac{4T_0}{3T} + \frac{T_0^4}{3T^4}\right)Q_r \qquad (16)$$

and E_{th} is the exergy exchanged for convection:

$$Ex_{th} = \begin{cases} \left(1 - \dfrac{T_0}{T}\right)Q_c & \text{for body} \quad \text{constant} \\ \left(1 - \dfrac{T_0}{T - T_0}\ln\dfrac{T_0}{T}\right)Q_c & \text{for body} \quad \text{variable} \end{cases} \text{temperature in the interaction with the environment} \qquad (17)$$

The chemical exergy load, Ex_{ch}, is evaluated as difference between the exergy of the inhaled air and the exhaled air, the last being considered saturated [38]:

$$Ex_{ch} = 1.608 R_w T_0 \left[Ex_0 - (\varphi_{0s} - \varphi_0)Ex_w - Ex_{0s}\right] \ln\left[\frac{(1 + 1.608\varphi_{0s})\varphi}{(1 + 1.608\varphi)\varphi_{0c}}\right] \qquad (18)$$

where R_w is the gas constant for the vapour, p is the pressure, φ is relative humidity ratio, while the subscript s means saturated, 0 reference state and c convective. Consequently, the total exergy Ex_{out}, that flow out from the body, results:

$$Ex_{out} = Ex_{sk} + Ex_{ch} = Ex_r + Ex_{th} + Ex_{ch} \qquad (19)$$

The input exergy Ex_{in} is the result of the metabolism, sensible heat and latent or wet exergy and it is the fundamental quantity to be evaluated in order to study the effect of the change of the environmental parameter on the human metabolism and, consequently, on the sensation of difficulty in case of bad thermal control in the art buildings:

$$Ex_{in} = \left(1 - \frac{T_{rm}}{T_{cr}}\right)M + R_w T_a \dot{m}_e \ln\varphi \qquad (20)$$

where the subscript rm means room, cr body core, w water (vapour), a air, e evaporative.

Consequently, the exergy lost Ex_λ in the process results:

$$\begin{aligned} Ex_\lambda &= Ex_{in} - Ex_{out} = \\ &= \left(1 - \frac{T_{rm}}{T_{cr}}\right)M + R_w T_a \dot{m}_e \ln\varphi - \left(1 - \frac{4T_0}{3T_{sk}} + \frac{T_0^4}{3T_{sk}^4}\right)R_r\left(T_{sk}^4 - T_{rm}^4\right) - \\ &- 1.608 R_w T_0\left[Ex_0 - (\varphi_{0s} - \varphi_0)Ex_w - Ex_{0s}\right]\ln\left[\frac{(1 + 1.608\varphi_{0s})\varphi}{(1 + 1.608\varphi)\varphi_{0c}}\right] - \\ &- \begin{cases} \left(1 - \dfrac{T_0}{T_{sk}}\right)R_c\left(T_{sk} - T_a\right) & \text{for} \quad \text{body constant} \\ \left(1 - \dfrac{T_0}{T_{sk} - T_0}\ln\dfrac{T_0}{T_{sk}}\right)R_c\left(T_{sk} - T_a\right) & \text{for} \quad \text{body variable} \end{cases} \text{temperature related to the environment} \end{aligned} \qquad (21)$$

with R thermal resistance and the subscripts, r and c, mean respectively radiative and convective respectively. Entropy generation can be related to the exergy loss as [12-14,40]:

$$S_g = \frac{Ex_\lambda}{T_a} \qquad (22)$$

where T_a is the environment temperature and can change. The principle of extremum entropy generation state that:

$$\delta S_g = 0 \qquad (23)$$

which allows to obtain the relation:

$$dEx_\lambda = \frac{Ex_\lambda}{T_a} dT_a = \frac{Ex_{in} - Ex_{out}}{T_a} dT_a \qquad (24)$$

which represents the response of the human body to the change of environmental temperature; introducing the following hypothesis:

1. $T_{rm} = T_a$;
2. T_{sk} = constant, in the first time of interaction;
3. T_{cr} = constant, in the first time of interaction;
4. φ = constant, in the first time of interaction;

and by suitable integration, it follows:

$$\begin{aligned}
\Delta Ex_\lambda = & \left(\ln \frac{T_{a2}}{T_{a1}} - \frac{T_{a2} - T_{a1}}{T_{cr}} \right) M + R_w (T_{a2} - T_{a1}) \dot{m}_e \ln \varphi - \\
& - \left(1 - \frac{4T_0}{3T_{sk}} + \frac{T_0^4}{3T_{sk}{}^4} \right) R_r \left(T_{sk}^4 \ln \frac{T_{a2}}{T_{a1}} - \frac{T_{a2}^4 - T_{a1}^4}{4} \right) - \\
& - 1.608 R_w T_0 \left[Ex_0 - (\varphi_{0s} - \varphi_0) Ex_w - Ex_{0s} \right] \ln \left[\frac{(1 + 1.608\varphi_{0s})\varphi}{(1 + 1.608\varphi)\varphi_{0c}} \right] \ln \frac{T_{a2}}{T_{a1}} - \\
& - \left(1 - \frac{T_0}{T_{sk}} \right) R_c \left(T_{sk} \ln \frac{T_{a2}}{T_{a1}} - \frac{T_{a2}^2 - T_{a1}^2}{2} \right)
\end{aligned} \qquad (25)$$

which represents the effect during the time between the environment temperature change and the human body answer. Considering that the metabolic effect of the temperature change can be evaluated as:

$$\Delta Ex_{in} = \Delta Ex_{out} + \Delta Ex_\lambda \qquad (26)$$

the input exergy change due to the environment temperature change becomes:

$$\begin{aligned}
\Delta Ex_{in} = & \left(1 - \frac{4T_0}{3T_{sk}} + \frac{T_0^4}{3T_{sk}{}^4} \right) R_r \left(T_{a2}^4 - T_{a1}^4 \right) - \left(1 - \frac{T_0}{T_{sk}} \right) R_c \left(T_{a2} - T_{a1} \right) + \\
& + \left(\ln \frac{T_{a2}}{T_{a1}} - \frac{T_{a2} - T_{a1}}{T_{cr}} \right) M + R_w (T_{a2} - T_{a1}) \dot{m}_e \ln \varphi - \\
& - \left(1 - \frac{4T_0}{3T_{sk}} + \frac{T_0^4}{3T_{sk}{}^4} \right) R_r \left(T_{sk}^4 \ln \frac{T_{a2}}{T_{a1}} - \frac{T_{a2}^4 - T_{a1}^4}{4} \right) - \\
& - 1.608 R_w T_0 \left[Ex_0 - (\varphi_{0s} - \varphi_0) Ex_w - Ex_{0s} \right] \ln \left[\frac{(1 + 1.608\varphi_{0s})\varphi}{(1 + 1.608\varphi)\varphi_{0c}} \right] \ln \frac{T_{a2}}{T_{a1}} - \\
& - \left(1 - \frac{T_0}{T_{sk}} \right) R_c \left(T_{sk} \ln \frac{T_{a2}}{T_{a1}} - \frac{T_{a2}^2 - T_{a1}^2}{2} \right)
\end{aligned} \qquad (27)$$

Therefore, it follows that the term useful to evaluate the effect on the metabolism is the variation of Ex_{in}, which results:

$$
\begin{aligned}
Ex_{in2} = {} & \left(1-\frac{T_{a1}}{T_{cr}}\right)M + R_w T_{a1}\dot{m}_e \ln\varphi + \left(1-\frac{4T_0}{3T_{sk}}+\frac{T_0^4}{3T_{sk}{}^4}\right)R_r\left(T_{a2}^4 - T_{a1}^4\right) - \\
& -\left(1-\frac{T_0}{T_{sk}}\right)R_c\left(T_{a2}-T_{a1}\right) + \left(\ln\frac{T_{a2}}{T_{a1}} - \frac{T_{a2}-T_{a1}}{T_{cr}}\right)M + R_w\left(T_{a2}-T_{a1}\right)\dot{m}_e \ln\varphi - \\
& -\left(1-\frac{4T_0}{3T_{sk}}+\frac{T_0^4}{3T_{sk}{}^4}\right)R_r\left(T_{sk}^4 \ln\frac{T_{a2}}{T_{a1}} - \frac{T_{a2}^4 - T_{a1}^4}{4}\right) - \\
& -1.608 R_w T_0\left[Ex_0 - (\varphi_{0s}-\varphi_0)Ex_w - Ex_{0s}\right]\ln\left[\frac{(1+1.608\varphi_{0s})\varphi}{(1+1.608\varphi)\varphi_{0c}}\right]\ln\frac{T_{a2}}{T_{a1}} - \\
& -\left(1-\frac{T_0}{T_{sk}}\right)R_c\left(T_{sk}\ln\frac{T_{a2}}{T_{a1}} - \frac{T_{a2}^2 - T_{a1}^2}{2}\right)
\end{aligned} \tag{28}
$$

The results can be evaluated for a human body characterized by the value reported in [1]: mass of 80 kg, air velocity of 0.1 ms^{-1}, relative humidity of 50%, body energy production of 68 $Wm^{-2}K^{-1}$, thermal resistance 0.14 m^2KW^{-1}, core body temperature 36.8°C, skin set temperature 33.7°C. The environmental temperature is considered around 20°C. The result is represented in Fig. 1. It must be pointed out that for less than 1°C of change (about 0.3% environment temperature change) the input exergy variation of about 0.05%, which means that about the 0.05% of the metabolism must be modified. For greater temperature changes the situation becomes more difficult to be supported by the body.

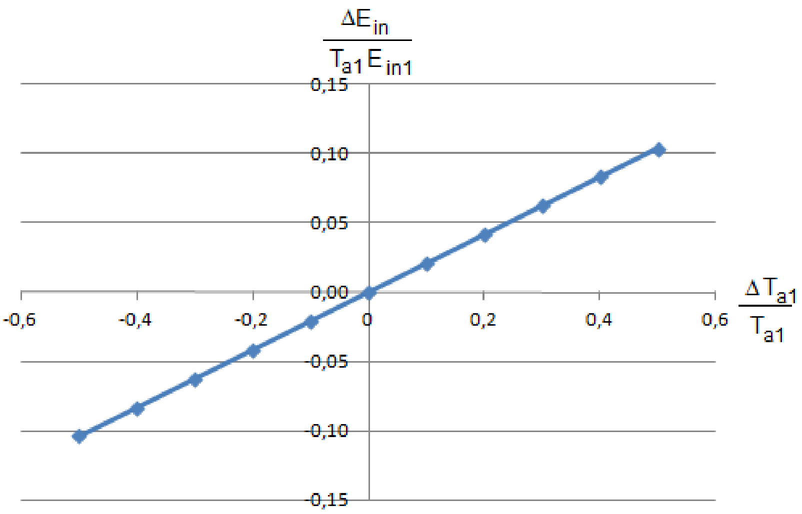

Fig. 1 – Input exergy percentage variation [$\%K^{-1}$] versus % change of the environmental temperature

5. Conclusions

Art buildings are not only the result of a cultural path, but also a technical physical application of thermal comfort control. Indeed, the human thermal environment is the result of the interaction of air temperature, air velocity and humidity. These parameters are the basis of the designing of comfortable environment.
Thermodynamics plays a key role in the analysis of systems in which energy transfer and energy transformation take place. In this paper a second law analysis of the thermal behaviour of the metabolism of a human body under environment variation is analysed by means of the extremum entropy generation. The novelty of the proposed method consists in the inclusion of all the significant processes that may influence the visitors' comfort in the metabolic model. The relevant result is that changes of temperature affects hardly the metabolism. Consequently, thermal and hygrometric control must be developed in art building with particular regards to the stationarity of the heating systems, in order to advantage the tourist in the visit. Further measurements of microclimate in museums and art exhibitions, combined with surveys aimed at visitors at the end of the visit on comfort during the exhibition along the rooms, may be

useful to confirm the present results and to improve the quality of museums' environments, guaranteeing the optimal conditions of conservation of the exhibited works and of the users' well-being.

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